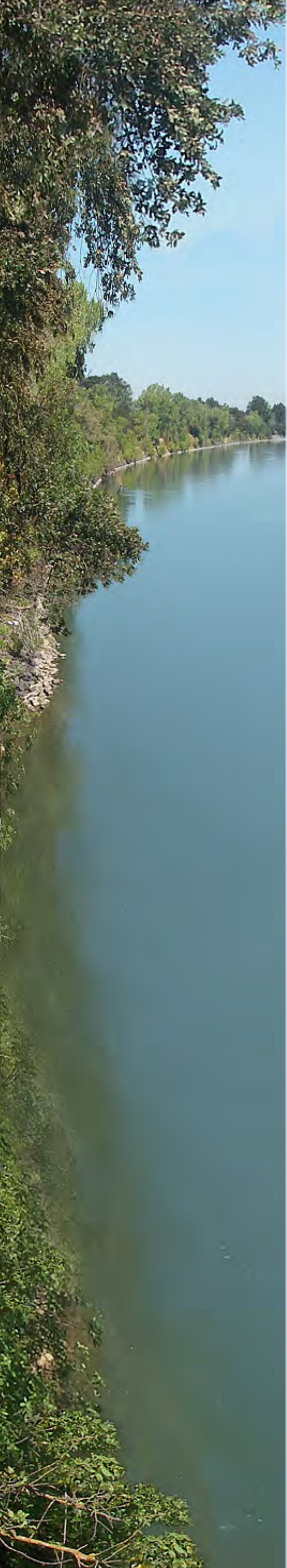

California Levee Vegetation Research Program

Influence of Tree Roots and Mammal Burrowing Activity on Levee Integrity:
Volume 4. – Field Evaluation of Burrowing Animal Impacts and Effectiveness of Remedial Measures

  

Diego Cobos Roa, Michelle Shriro, Nicholas Sitar and Jonathan D. Bray
Department of Civil and Environmental Engineering
University of California
Berkeley, CA 94720

Grant funding provided by:
The California Department of Water Resources (Contract No. 4600008761)
and the Sacramento Area Flood Control Agency (Contract No. 984)

January 2014

Geotechnical Engineering
University of California, Berkeley
Report UCB GT 13-03 vol. 4

Sponsoring/Advisory Agencies of the California Levee Vegetation Research Program

California Levee Vegetation Research Program

Influence of Tree Roots and Mammal Burrowing Activity on Levee Integrity:
Volume 4. – Field Evaluation of Burrowing Animal Impacts and Effectiveness of Remedial Measures

Diego Cobos Roa, Michelle Shriro, Nicholas Sitar and Jonathan D. Bray
Department of Civil and Environmental Engineering
University of California
Berkeley, CA 94720

Grant funding provided by:
The California Department of Water Resources (Contract No. 4600008761)
and the Sacramento Area Flood Control Agency (Contract No. 984)

January 2014

Geotechnical Engineering
University of California, Berkeley
Report UCB GT 13-03 vol. 4

SUMMARY

Two sites on levees with known burrowing animal infestations were selected in order to study the architecture and the extent of animal burrow complexes, as well as the efficacy of current California Department of Water Resources burrow grouting techniques. The sites were selected so as to represent different site conditions, both in terms of material properties and in terms of the dominant burrowing animal species. A sandy levee site was chosen to represent a relatively porous and permeable levee infested with California ground squirrel (*Otospermophilus beecheyi*) and a clayey levee was selected to represent a more cohesive, low permeability embankment infested predominantly by pocket gophers (*Thomomys bottae)* and a minor California ground squirrel population.

Large burrow complexes were encountered at both test sites extending for several tens of meters on both landslide and waterside slopes. The location and the extent of the burrow networks were dominated by the presence of an interface between loose and stiff layers where the latter formed a stable roof, while an underlying looser or sandy material contributed to easy digging. The density of the burrows at the two test sites was found to be directly correlated to the proximity of an available food source. While the burrow complexes were quite extensive, complete penetration of the levee was found in only one instance. This particular burrow in the clayey levee, extended from the waterside to the landside at approximately mid-slope elevation, coinciding with past reports of piping (internal erosion) on this site.

The selected sites also presented very different histories of treatment. The sandy levee was not routinely grouted and baiting with poisoned bait and propane gas explosions were used to control the burrowing animal population. In contrast, the clayey levee was routinely grouted with cement bentonite grout to both control the burrowing animal population and to maintain the integrity of the levee. Two rounds of grouting, first with cement-bentonite mix and then with polyurethane were performed at each site to evaluate the efficacy of using the cement-bentonite grout and also to facilitate the mapping of the burrows. The cement-bentonite grout was injected directly into openings of the burrows, while the polyurethane was injected on a grid. The results of the grouting program showed that a majority of the burrows were filled with the cement-bentonite mix and only a small number of burrows were filled exclusively with the polyurethane grout, likely because no surface expression of these burrows were present at the time of initial grouting. These observations confirm that the current cement-bentonite injection practice used by the California Department of Water Resources is a useful tool in grouting most of the large active burrows on levees, as long as regular maintenance is performed. However, there is always a possibility that large holes are missed and these holes may be completely penetrating the embankment. Thus, grouting has to be supplemented by regular patrolling and careful maintenance of field logs of burrowing activity and grout takes/volumes.

ACKNOWLEDGEMENT

This study was performed collaboratively as part of the California Levee Vegetation Research Program (CLVRP) and was sponsored by the local, state, and federal agencies of the California Levees Roundtable through grants from Sacramento Area Flood Control Agency (SAFCA Contract No. 984), and the California Department of Water Resources (DWR Contract No. 4600008761). A great deal of support was provided by these agencies during our studies. The authors wish to thank Mr. Peter Buck, Program Manager for the CLVRP, consultant Mr. Mick Klasson, Ms. Cassandra Musto and Mr. Roy Kroll of the CDWR and Ms. Laura Kaplan of the Center for Collaborative Policy for their invaluable help. We would like to thank the entire CLVRP team for their support and assistance during this research.

The field investigations of the animal burrowing activity and of the efficacy of the grouting techniques were possible thanks to the interest and contributions of the local maintaining agencies and landowners who provided access and support to our team. Special thanks go to Mr. Max Sakato, Mr. Jack Bailey, Mr. Mike Gardner and the staff of Reclamation District 1500. Their patience, support, and contributions are greatly appreciated.

Prof. Alison Berry of UC Davis shared field equipment with us during our studies; Mr. Joe Gray, Ms. Siobhan O'Reilly-Shah, Mr. Nick Broussard, Mr. Richard Montalvo and Mr. Cale Crawford of ENGEO Inc. greatly contributed to the field efforts. Urethane grouting employed in the mammal burrow characterization was provided by Mr. Gregg Day. All T-LiDAR work for the project was performed by Dr. Gerald Bawden with assistance from Mr. James Howle and Ms. Sandra Bond of the USGS. Key logistic and field support was provided by Mr. Roy Kroll and Mr. Al Romero from the California Department of Water Resources. We thank them all for their insights, hard work, and commitment to the project.

CONTENTS

SUMMARY……i

ACKNOWLEDGEMENT……ii

1 INTRODUCTION 4

2 TESTING METHODOLOGY... 4

2.1 SITE SELECTION 4

2.2 SITE SURVEY 5

2.3 GROUTING PROGRAM.. 5

3 SITE 1: SANDY LEVEE 10

4 SITE 2: CLAYEY LEVEE SITE... 15

5 EXCAVATION AND SURVEYING 22

5.1 SITE 1: SANDY LEVEE 22

5.1.1 WATERSIDE BURROW SYSTEM 23

5.1.2 LANDSIDE BURROW SYSTEM 26

5.2 SITE 2: CLAYEY LEVEE 30

5.2.1 LANDSIDE BURROW SYSTEM 30

5.2.2 WATERSIDE SYSTEM.. 32

6 SIGNIFICANCE OF THE COMPLETELY PENETRATING BURROW................................. 33

7 SUMMARY OF RESULTS AND OBSERVATIONS 34

8 EFFECTIVENESS OF THE CEMENT-BENTONITE GROUT 37

9 REFERENCES... 38

LIST OF FIGURES

Figure 2-1. Reference targets used for aligning T-LiDAR scans 6

Figure 2-2. DWR portable grout mixer for field tests.. 6

Figure 2-3. Typical DWR grouting procedure... 7

Figure 2-4. Experiment setup: (a) injection tubing prior to installation, (b) installation of tubing using jackhammer 8

Figure 2-5. Experiment setup: example of triangular grid of chemical injection points 8

Figure 2-6. Experiment setup: (a) double-stroke pump system, (b) 'F assembly' injection device 9

Figure 2-7. Flow chart of polyurethane grout injection process 9

Figure 2-8. View of chemical grout injection procedure 10

Figure 3-1. Cross section of the sandy levee 11

Figure 3-2. Typical active squirrel burrows on landside slope of the sandy levee 11

Figure 3-3. Largest active squirrel burrows on waterside slope of the sandy levee 12

Figure 3-4. Plan view of surveyed burrows at the sandy levee site 13

Figure 3-5. Plan view of cement-bentonite and polyurethane injection points on the sandy levee site 14

Figure 3-6. Simplified cross section of the sandy levee 15

Figure 4-1. Cross section of the clayey levee 16

Figure 4-2. High water on the clayey levee site during 1998. Images courtesy Al Romero, DWR 17

Figure 4-3. Evolution of grout quantities on the clayey levee site (data provided by Al Romero, DWR) 18

Figure 4-4. Location of burrows on landside slope of the clayey levee. Pink flagging indicates location of undifferentiated burrows, green flagging indicates burrows historically grouted with cement-bentonite by DWR 19

Figure 4-5. Typical squirrel burrows on waterside slope of the clayey levee 20

Figure 4-6. Plan view of identified burrows at the clay levee site 20

Figure 4-7. Map of grout injection points at the clayey levee site 21

Figure 4-8. Embankment cross section of the clayey levee. 22

Figure 5-1. Exposed burrow system near waterside toe of the sandy levee 23

Figure 5-2. Continuation of waterside burrow into the levee on the sandy levee 24

Figure 5-3. Close up of den near waterside toe of the sandy levee 25

Figure 5-4. New hole after cement-bentonite grout on waterside toe of the sandy levee Site. (a) shows the location of the new burrow and (b) shows the partially excavated open burrow below the cement-grouted main tunnel........ 25

Figure 5-5. Aerial view of east edge of main complex near landside edge of crown 27

Figure 5-6. Oblique view looking upstream of main complex near landside edge of crown 27

Figure 5-7. Lateral view of landside slope burrow system........ 28

Figure 5-8. Cross section showing LiDAR data on the sandy levee........ 29

Figure 5-9. Close-up of landside burrow system (a) shows a cross section view, (b) a front view .. 29

Figure 5-10. Views of the waterside burrow system 30

Figure 5-11. View of excavated landside slope on the clayey levee. 31

Figure 5-12. View of completely penetrating burrow........ 31

Figure 5-13. View looking north of completely penetrating burrow........ 32

Figure 5-14. Oblique view of waterside burrow system........ 33

Figure 6-1. Cross section view of completely penetrating burrow through the clayey levee........ 34

Figure 6-2. Plan view of burrow system in the clayey levee 34

Figure 7-1. Layer interface facilitating burrowing in the sandy levee. 35

Figure 7-2. New burrows on landside slope of the reconstructed sandy levee 36

Figure 7-3. Ungrouted burrows in the sandy levee: (a) A burrow near Level 1 of the large landside burrow complex, and (b) An ungrouted burrow to the west of the same complex........ 36

LIST OF TABLES

Table 3-1. Approximate cement-bentonite grout volumes used........ 14

Table 3-2. Index soil properties at the sandy levee site........ 15

Table 4-1. Index soil properties at the clayey levee site 21

Table 8-1. Summary of grout volumes 37

1 INTRODUCTION

Two different sites were chosen for this study in order to capture the effects of animal burrowing in levees with different composition in different environments. The first site was a section of a sandy levee with an active California ground squirrel *(Otospermophilus beecheyi)* infestation, and with minimal maintenance and mitigation practices in place. The second site was a clayey levee where yearly maintenance activities are undertaken by the California Department of Water Resources (DWR) and, consequently, the effects of the burrowing activity were considered minor. Thus, these two field studies were aimed to achieve two objectives:

- Assess the extent and architecture of burrow networks under the two limiting conditions of: (1) no maintenance and regular (yearly) baiting; and (2) regular (yearly) grouting.
- Study the efficacy of current DWR grouting techniques by injecting a cement-bentonite grout into the largest burrows, and a chemical grout to fill remaining void spaces missed by the cement grout.

2 TESTING METHODOLOGY

2.1 SITE SELECTION

The field sites were selected in consultation and evaluation of candidate sites with personnel from SAFCA, DWR and members of the advisory board for the CLVRP. The selection of the sites was based on the following criteria:

- Degree of infestation: A site with an active infestation was required to show the effect of minimal maintenance or animal control on the size and extent of the burrow system, while a second site where periodic maintenance takes place was selected in order to observe the effects of regular maintenance practices.
- Burrowing species: California ground squirrels and Botta's pocket gophers (*Thomomys bottae*) were the target species for both tests performed. As described in Volume 1 of this report, smaller species are likely to have less influence on the performance of a levee, and larger species with potentially larger diameter burrows have been found to be much less abundant than California ground squirrels and Pocket gophers (Van Vuren, 2011).
- Soil conditions: The sites were targeted so the infestations were encountered in different materials. The embankment at the site with minimal animal control measures consisted mainly of loose sands with interbedded clay layers, while the maintained site consisted of a clay embankment.

2.2 SITE SURVEY

The first step in the site evaluation consisted of surveying all existing active and inactive burrows by installing a coordinate grid along the levee slopes and crown, measuring the size of the main holes encountered, and documentation of all other important features, such as stratigraphic contacts, cracks along the levee crown and slopes, including the presence of vegetation.

After the grid was installed, survey flags were placed next to each hole and an initial high-resolution ground based LiDAR (T-LiDAR: Tripod Light Detection and Ranging) base scan was performed so a three dimensional image of the levee prior to the test was available. A local reference frame was established for the T-LiDAR systems by installing several spherical benchmarks mounted on a a threaded rod pushed to refusal, and a set of six 4-inch PVC crosses outside the study area such that a minimum of six spherical (Figure 2-1) or PVC targets could be seen in each scan to optimize post-processing and aligning processes. Two types of T-LiDAR systems were used: an *Optech* ILRIS device, which captures infrared contrasts on the soil at a scan density of 2 to 3 millimeter spot spacing, or 2,500 data points per square meter; the second survey device employed on the animal burrow tests was a *Faro (what?) LiDAR?*, which is able to capture real red-green-blue (RGB) color of each scanned point, generating a 3D colored representation of the scanned area. The flags next to each hole were installed with a two to three centimeter long reflective strip that produces a signal spike on the T-LiDAR data (Cobos Roa et al., 2012) so the exact location of the holes in the study area were captured by the baseline laser scan.

2.3 GROUTING PROGRAM

The first round of grouting was performed using the typical cement-bentonite grout mix employed by the DWR and local maintenance districts in their periodic grouting campaigns. This mix was a relatively viscous grout containing 5-10% bentonite. This phase of the grouting program used a portable grout rig (Figure 2-2), which consisted of a small drum fixed to a board, so a small forklift could transport it, and fitted with a pump, hoses and valves to allow the desired amount of mixed grout to flow by applying a small amount of pressure (approximately 0.5 psi [3.4 kPa]). Inside the drum, the mix of cement, bentonite and water is achieved manually, or a mix on-site cement truck can be used to pour the cement into the mix.

Figure 2-1. Reference targets used for aligning T-LiDAR scans

Figure 2-2. DWR portable grout mixer for field tests

Once the cement-bentonite mix is prepared, holes typically targeted during regular grouting operations (8 cm in diameter and larger) were filled until grout flowed back out of the hole or out of a nearby hole, at which point the hole was plugged using a burlap bag (Figure 2-3).

The approximate time it took for each hole to be filled was recorded and using average flow quantities coming from the pump, the volume of grout used was estimated. If cement-bentonite grout was observed flowing out of one or more holes around the injection point, its locations were recorded.

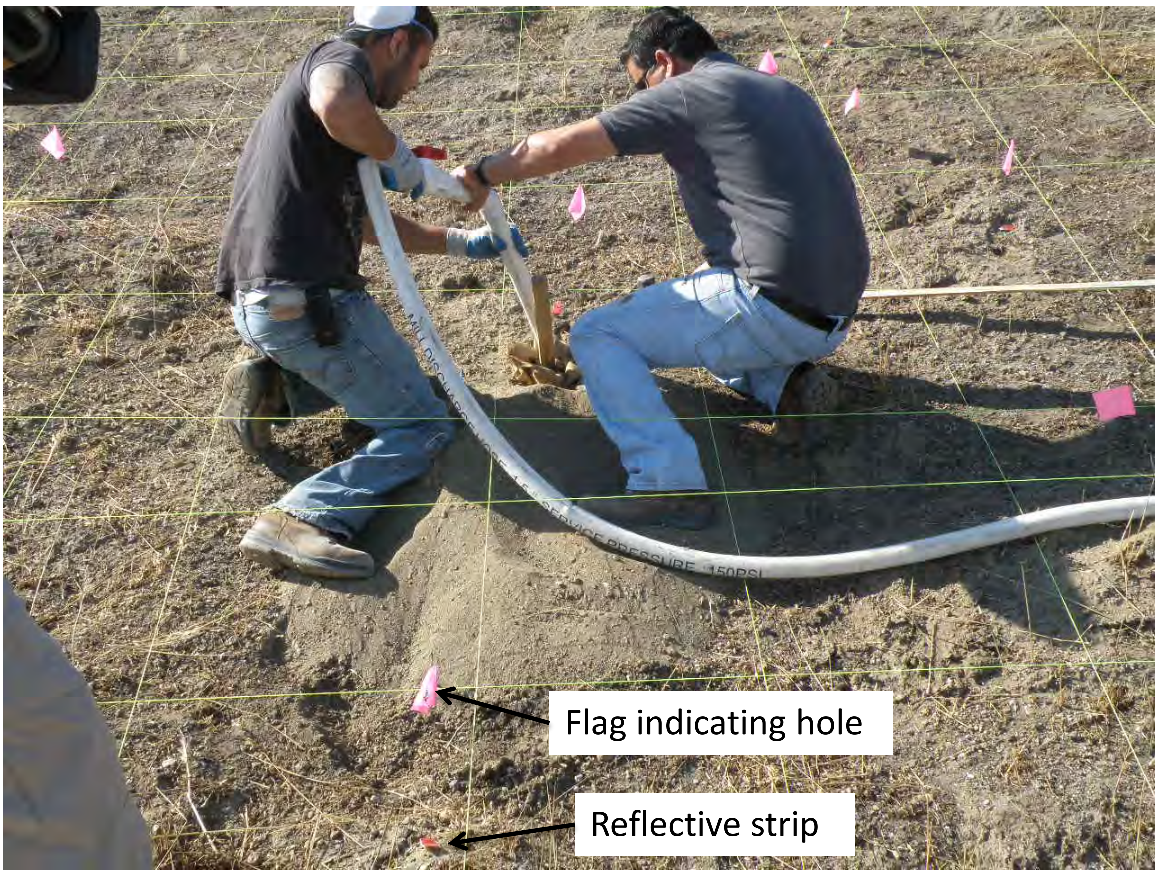

Figure 2-3. Typical DWR grouting procedure

Several days after the cement-bentonite grouting program was completed, another round of grouting was performed, this time using a polyurethane-based grout. The chemical mixture and injection procedure was similar to one used in 2008 after the levee failure in Fernley, Nevada (described in Volume 1 of this report). Grout consisted of a mixture of ten parts pink-dyed water and one part additive composed by Stratathane ST-504 injection resin from Strata-Tech Inc. and Sika® concrete bonding adhesive.

The result was a very fluid hydrophilic solution capable of flowing through the pores of coarse grained materials and fissures in the fine-grained soil until a large discontinuity such as a burrow was encountered, at which point the polyurethane flowed into the opening and quickly filled it. The mixture expanded while curing thus creating a tight seal.

The polyurethane grout was injected into the soil using 2 cm diameter, 1.5 meter (5 feet) long steel tubing with holes drilled along the lower 1 meter (3 feet) of tube (Figure 2-4). The pipes were inserted into the soil using a jackhammer in a 1.2 m (4 feet) on center triangular grid pattern (Figure 2-5), and several additional pipes were inserted near large active holes where large amounts of cement-bentonite grout were used during the first phase of the grouting program.

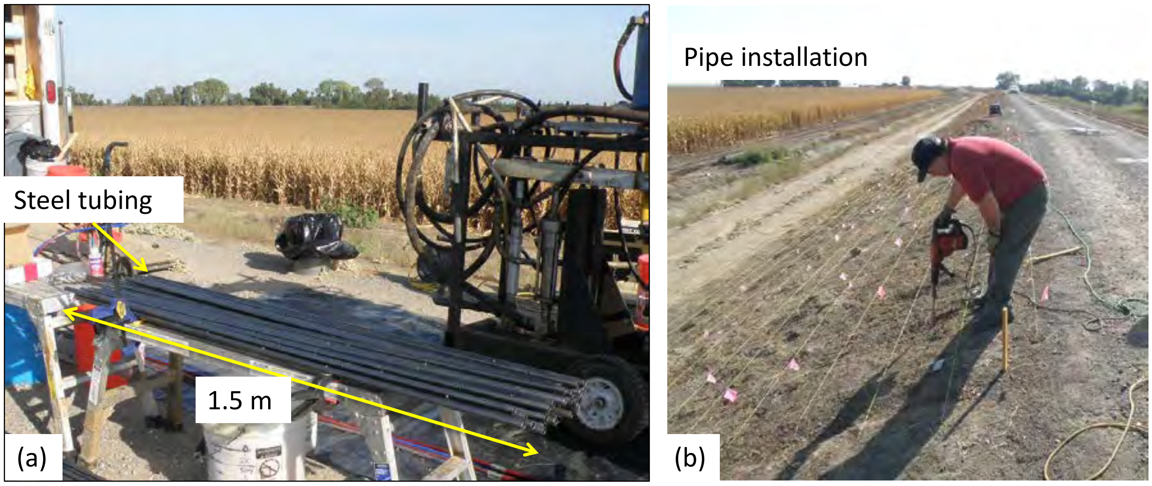

Figure 2-4. Experiment setup: (a) injection tubing prior to installation, (b) installation of tubing using jackhammer

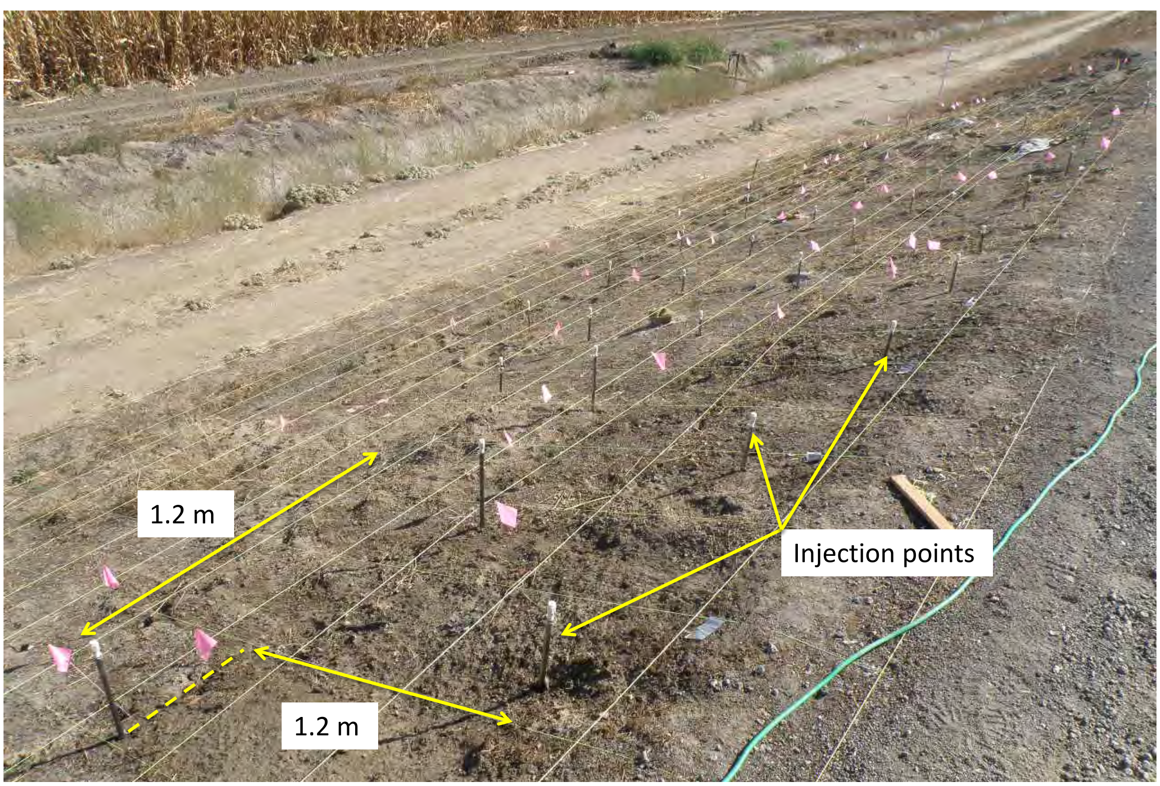

Figure 2-5. Experiment setup: example of triangular grid of chemical injection points

The polyurethane grout was pumped using a double stroke pump (Figure 2-6a) which regulates the amount of water and additive being transferred to the injection gun, commonly known as an ‘F assembly’ (Figure 2-6b). This gun joins the water and additive lines in a 0.5 cm diameter tube which mixes the two flows prior to entering each injection tube (Figure 2-7).

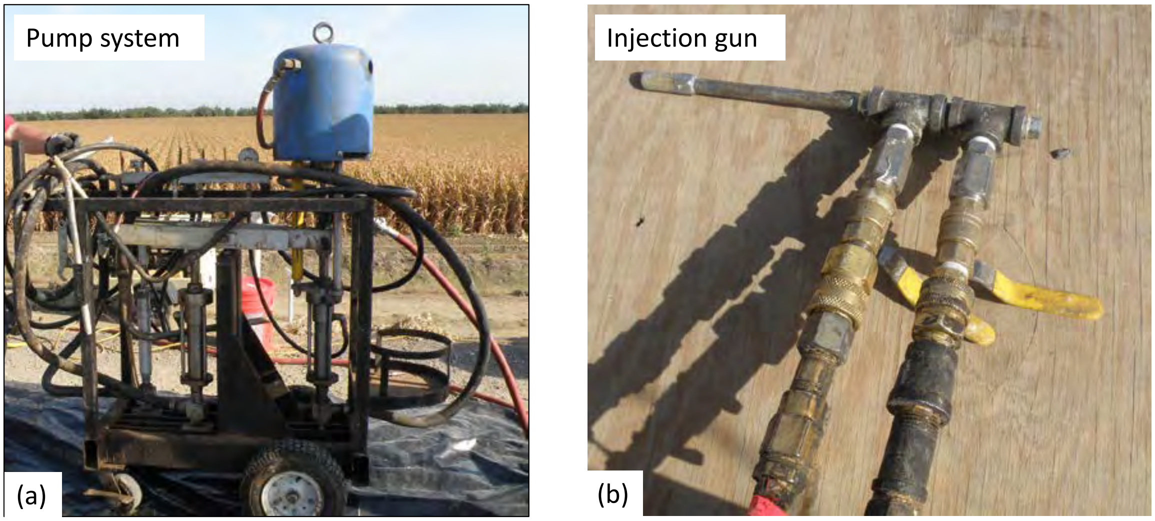

Figure 2-6. Experiment setup: (a) double-stroke pump system, (b) 'F assembly' injection device

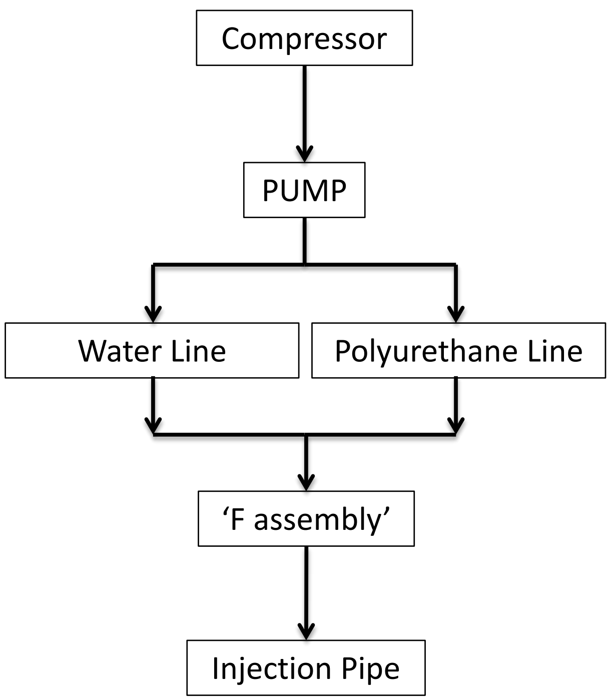

Figure 2-7. Flow chart of polyurethane grout injection process

The polyurethane grout was then pumped into each injection point (Figure 2-8) until grout flowed back up around the tubing, out of the soil nearby the injection port, or out of a nearby burrow. Injections started at the lower line of pipes and moved upslope to form a barrier and decrease the amount of grout and water mix flowing downslope and away from the levee toe. This process generally took one to three minutes for each injection point, but some areas near the largest burrows took up to ten minutes per point.

Figure 2-8. View of chemical grout injection procedure

3 SITE 1: SANDY LEVEE

The first site was a levee bordering the eastern margin of the Sacramento River, several miles upstream of Sacramento, California. Figure 3-1 shows the cross section and the relative location of the embankment from the river and the available food source present approximately ten meters from the landside toe.

No periodic grouting or baiting practices are in place at this site. Rodent control measures typically performed by the reclamation district in charge of maintaining this levee consist of the use of a propane gun to internally collapse active burrows, filling of the blasted hole using hand tools, and occasional baiting. During inspection of the area several large active California ground squirrel burrows were encountered along a stretch of the levee adjacent to a cornfield, and a 20 meter (60 feet) long segment encompassing some of the largest burrows within this reach was selected for the test.

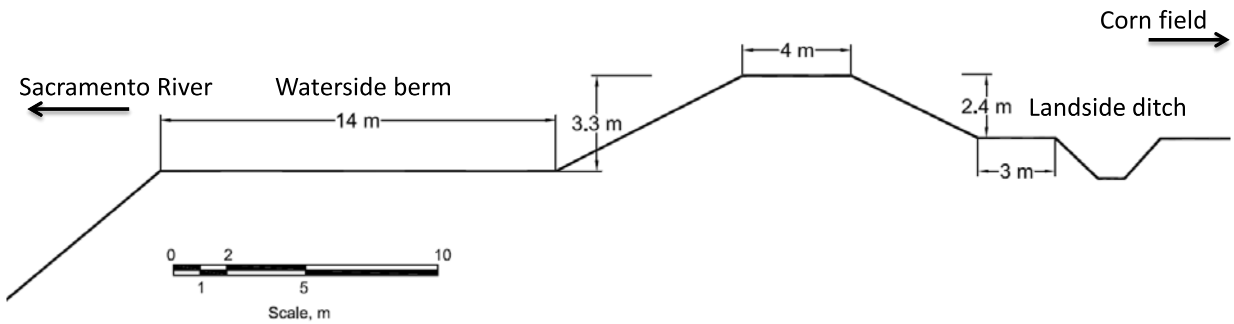

Figure 3-1. Cross section of the sandy levee [1 m: 3.28 ft]

On the landside slope (Figure 3-2), several large active burrows were observed mid slope and towards the levee crown, with 'porches' of ejected material exceeding one meter in downslope length. Typical active burrow diameters ranged between 8 and 20 centimeters (0.3 and 0.7 ft), indicating the burrowing species was ground squirrel, which was confirmed later when several ground squirrels were observed emerging from nearby burrows. The upper bound of the diameter appears to be large for the common California ground squirrel, and can be explained by the fact that the levee material lacks cohesion or cementation and collapses easily, therefore the large size of some holes is likely due to re-digging of previously smaller burrows (Van Vuren, 2012).

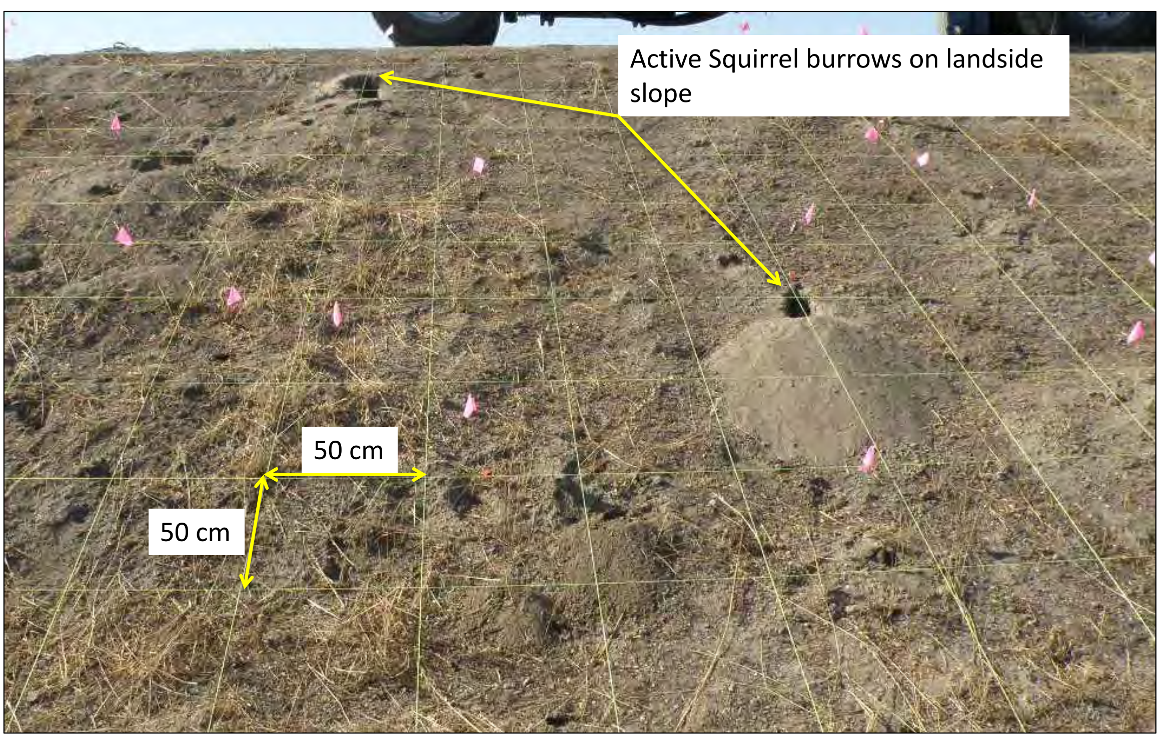

Figure 3-2. Typical active California ground squirrel burrows on landside slope of the sandy levee

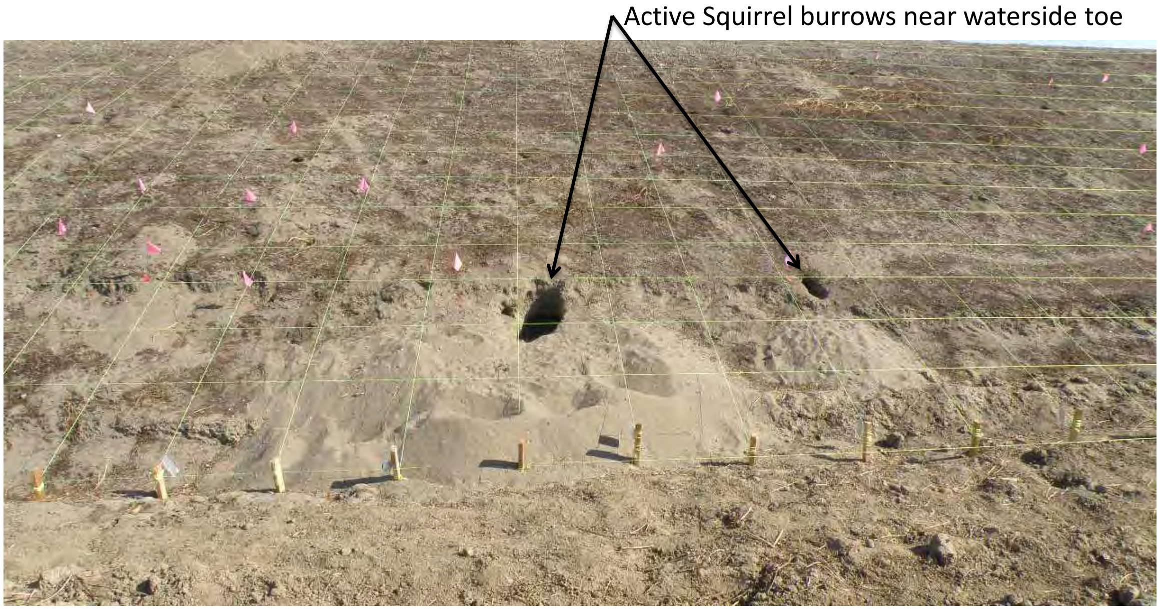

Figure 3-3. Largest active California ground squirrel burrows on waterside slope of the sandy levee

Figure 3-3 shows a view of the main burrows on the waterside slope. Two large burrows with an entrance diameter between 20 and 30 centimeters (0.7 and 1 ft) were observed near the waterside toe, and showed a large cone of ejected material. Other burrows along the waterside slope were generally small or inactive. Seventy two burrows were surveyed on the landside slope; thirty four burrows were encountered on the waterside slope, and six along the crown of the levee. The marked difference between landside and waterside slope is likely attributable to the proximity of the food source to the landside slope, and to layering of the levee embankment. The surveyed holes are indicated by pink flags on Figure 3-2 and Figure 3-3, and are shown in plan view on Figure 3-4. The plan view shows active ground squirrel burrows and all other holes where no differentiation of activity and species could be made because of recent burning of the levee slopes, which might have removed the material from the porches, and partially or completely collapsed some holes.

A burrow was classified as active based on the presence of material ejected downslope of the entrance, food waste and/or footprints in the vicinity of the entrance. A total of 14 active ground squirrel holes were surveyed on the landside slope, one on the crown near the landside hingepoint and six on the waterside slope. Inactive burrows showed a similar trend; 58 inactive or collapsed holes were observed on the landside slope, while 19 were found on the waterside slope.

Figure 3-5 overlays the surveyed burrows and the injection points for the two types of grout used in this study. The green squares indicate the fourteen burrows where cement-bentonite grout was injected, and green arrows indicate instances when grout flowed out of holes adjacent to a burrow being grouted. The time required to fill every hole was recorded, and volumes were estimated using average flow quantities from the portable equipment (0.01 m^3/s) used by DWR (Table 3-1). Typical DWR grouting activities target the largest holes with a clear and open surface expression; consequently only fourteen holes were grouted using this technique and all other holes were dismissed because they were either too small or collapsed near the entrance.

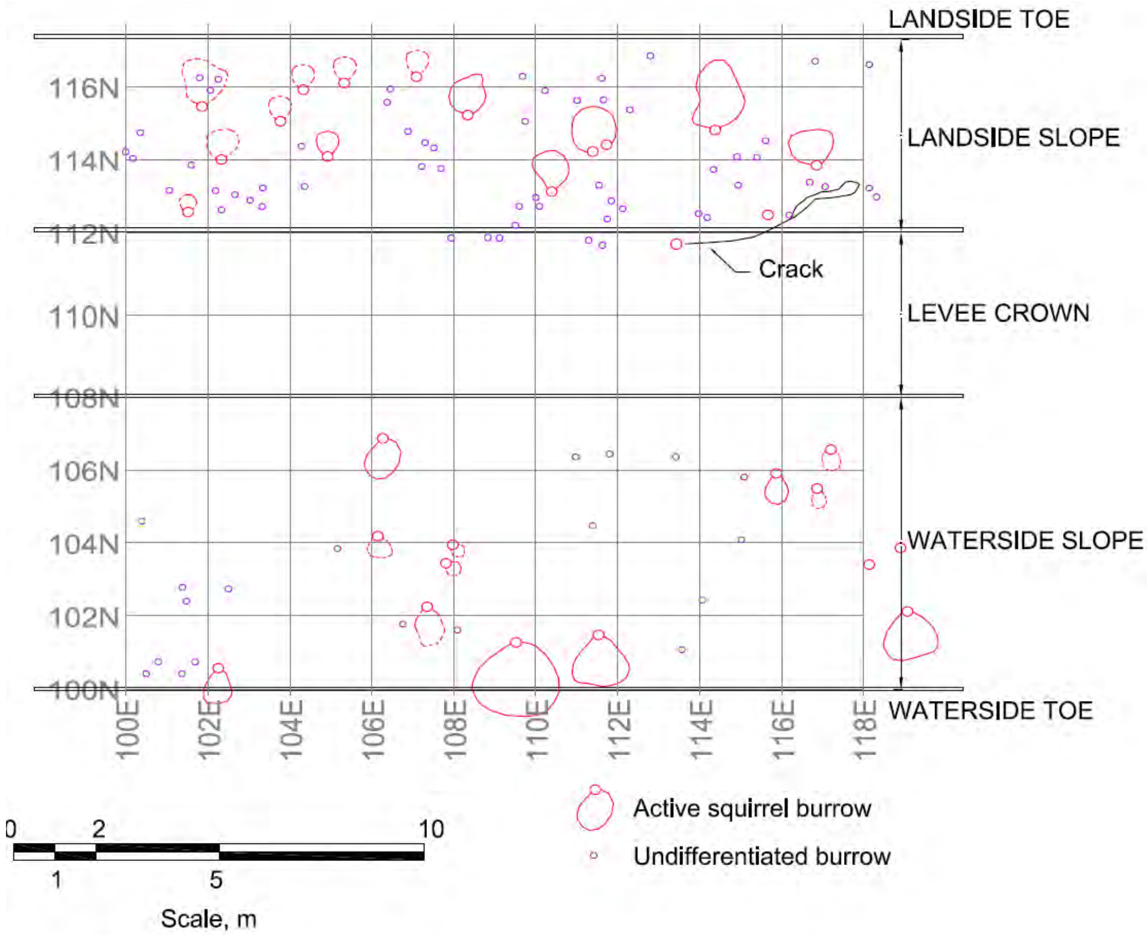

Figure 3-4. Plan view of surveyed burrows at the sandy levee site

A total of 140 polyurethane injection points were used to cover the area under study (Figure 3-5). Each point was injected with the chemical grout following the procedure described in previous sections, and similar to the cement-bentonite grout, times (and consequently volumes) of injection varied between injection points.

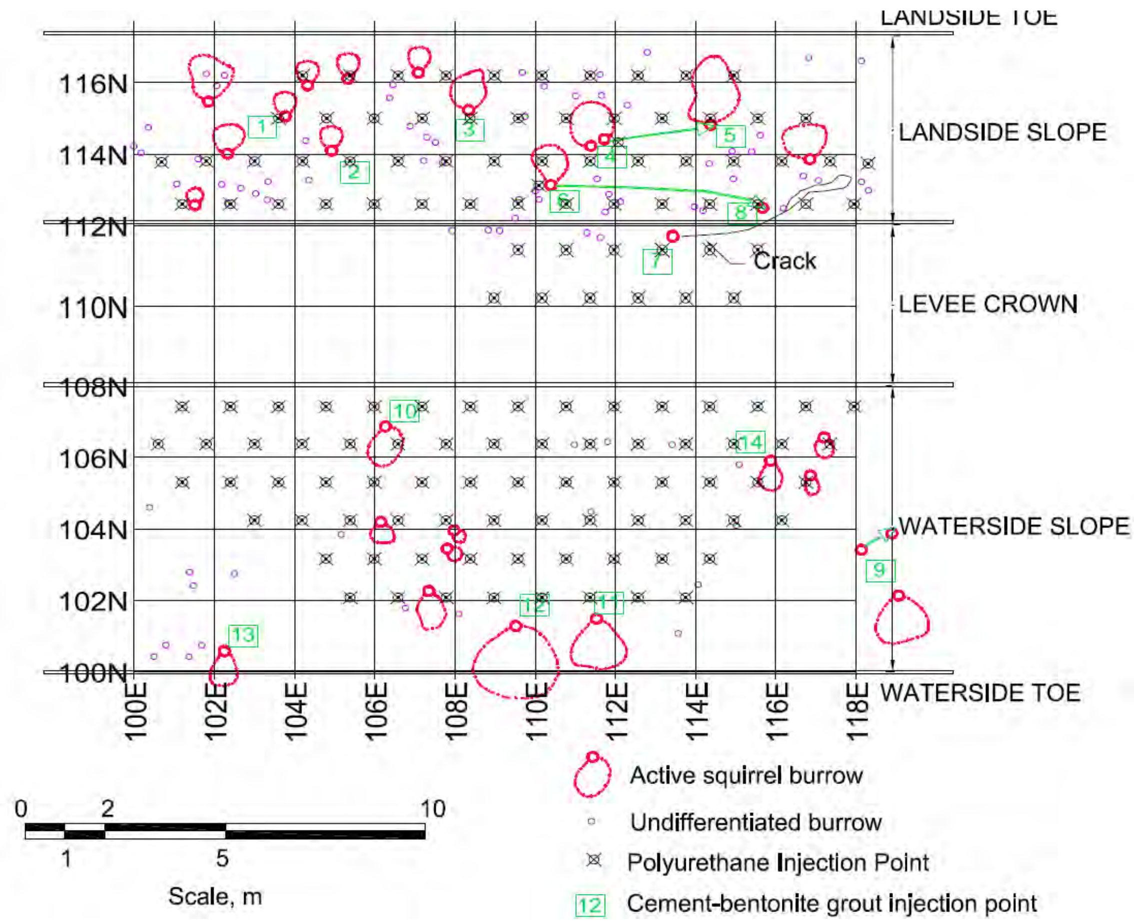

Figure 3-5. Plan view of cement-bentonite and polyurethane injection points on the sandy levee site

Table 3-1. Approximate time required to fill holes with cement-bentonite grout

Hole Number	Time required to fill hole (sec)
1	15
2	35
3	15
4	900
5	25
6	10
7	20
8	420
9	180
10	60
11	210
12	60
13	20
14	30

Index soil properties were estimated for the site prior to excavation. Disturbed soil samples were retrieved using bag samples. The objective of the testing program was to obtain general index properties that allow basic geotechnical characterization of the levee embankment at the test site.

Table 3-2 shows the summary of index properties estimated from four samples obtained at different points on the levee embankment.

Table 3-2. Index soil properties at the sandy levee site

Sample	% Fines	% Sand	% Gravel	Water Content	USCS
				(%)	
LS-1	10	90	0	16.5	SP-SM
LS-2	15	85	0	-	SM
WS-1	17	83	0	-	SM
WS-2	61	39	0	23.0	ML

LS: Landside slope, WS: Waterside slope, Unified Soil Classification System (USCS), SP-SM: Poorly graded sand with silt, SM: Silty sand, ML: Silt

Samples LS-1, LS-2 and WS-1 correspond to the majority of the levee material, composed of silty sand with a mean grain size of 0.3 millimeters and 13 percent fines. The last sample was retrieved from a thin stiff silt seam near the waterside toe slope area. Most of the long burrows found during post grouting excavation were encountered along the interface between these stiff seams and the loose sands. A simplified cross section for the Sandy Levee Site is shown on Figure 3-6.

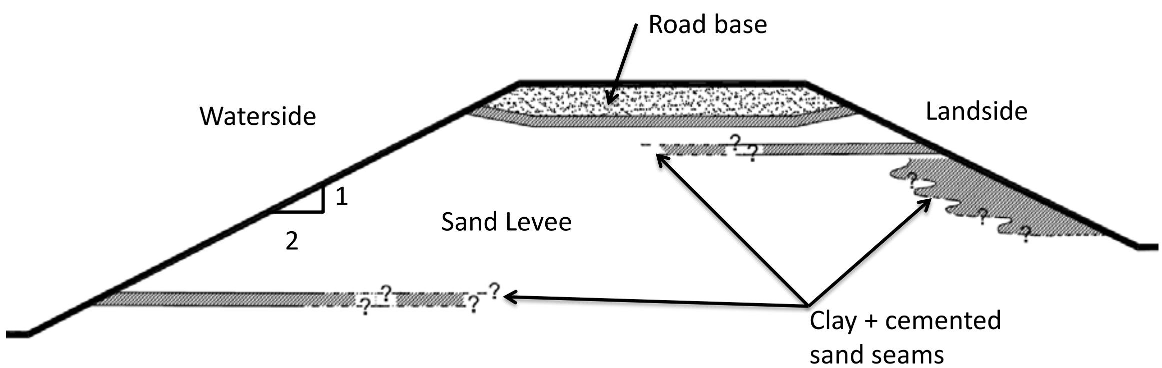

Figure 3-6. Simplified cross section of the sandy levee

4 SITE 2: CLAYEY LEVEE SITE

The second site was a smaller levee along the west levee of Cache Creek north of Woodland, California. Similar to the sandy levee, this site also had an active small mammal food source very near the landside toe of the levee; Figure 4-1 shows the approximate cross section at this site. The creek channel is located 20 meters away from the levee and has incised into its bed therefore the levee isinfrequently wetted during the flood season.

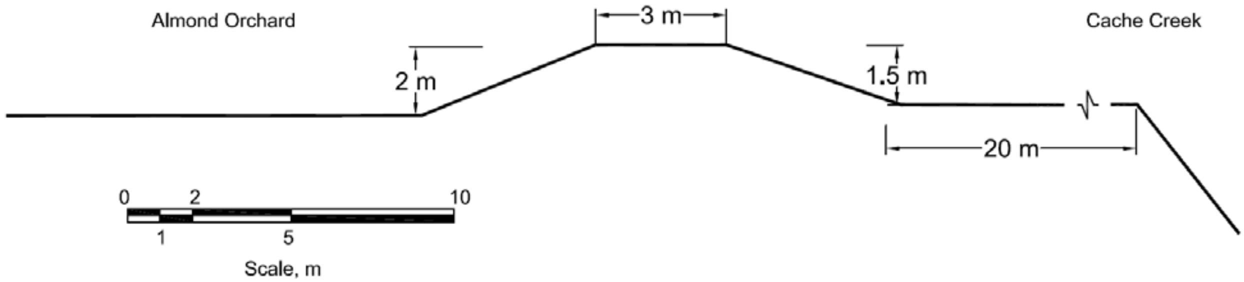

Figure 4-1. Cross section of the clayey levee

This site is of great importance to the history of grouting practices in California. During the floods of March 1998, this levee experienced water levels within 0.5 meters of the crown (Figure 4-2a). Sustained high water resulted in several sand boils and through-seepage on the clayey embankment (Figure 4-2b, c and d). This near failure was attributed to the presence of mammal burrows, which led to the beginning of current DWR grouting and maintenance programs. Since 1998, this levee has been used as a test site by the DWR, to perfect grouting techniques and mix compositions. Grouting takes place at the end of the spring season, and records of grouting volumes and number of burrows have been kept and were provided by DWR personnel (Figure 4-3). The figure shows that the volume of grout required to fill active or new burrow holes along this stretch of levee decreases every year despite having a food source next to the levee. The fact that several holes were flowing muddy water during the 1998 flood indicates that some of these burrows were completely penetrating the embankment and piping was occurring.

DWR (2009) concluded that there were holes completely penetrating the levee prism in the study area, and these holes tend to be located in the upper portion of the levee representing a significant risk for stability if not remediated. The study provides several important observations:

- *"Rodent colonies and individual holes appear to increase in size each year if not backfilled.*
- *Surface treatments such as dragging and track walking levee slopes leave hidden voids within levees. Consequently, such activities should be performed after grouting is completed.*
- *Levee reconstruction to address rodent damage is not economically practical for individual holes given the scope of the rodent problem.*
- *Squirrel population varies greatly from year to year and is dependent on weather. High concentrations of squirrels are observed after mild winters.*

- *After a colony of squirrels is eradicated, the burrow systems are quickly filled with juvenile squirrels from adjacent locations.*
- *Best eradication results are achieved when state efforts have been coordinated with activities of local growers".*

The data in Figure 4-3 suggests that even though the number of burrows encountered along the levee reach under study had increased by approximately 300%, the amount of grout used per hole declined five-fold. Not shown on the plot is the amount of labor hours per hole, which declined from about two man-hours in 2000 to less than 0.5 in 2004. These results suggest that the adoption of a periodic burrow grouting program can mitigate the likelihood of a large burrow or network of burrows from penetrating a levee, along with a decreasing maintenance cost.

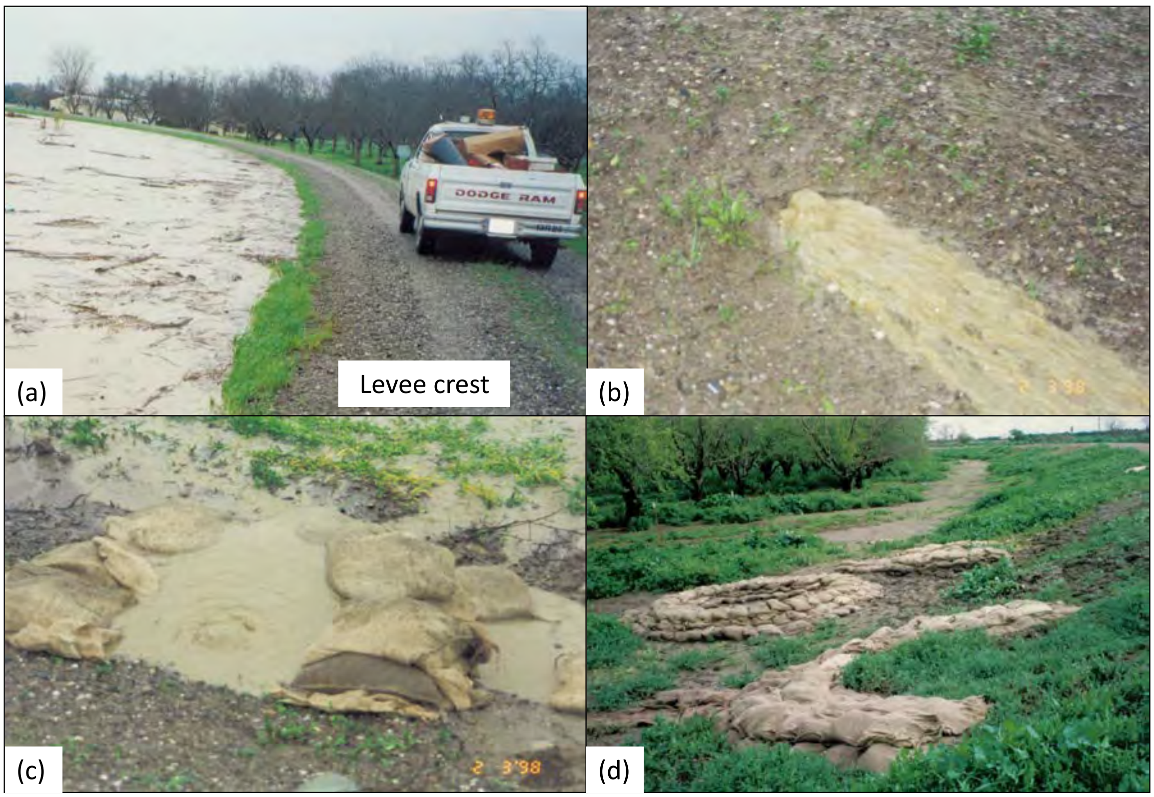

Figure 4-2. High water on the clayey levee site during 1998. Images courtesy Al Romero, DWR

In general burrowing activity at the clayey levee site observed during this study wasmainly by Pocket gophers, with a few isolated California ground squirrel burrows. Typical burrows had diameters ranging from five to ten centimeters, and were mostly concentrated in the upper half of both landside and waterside slopes, coinciding with a strip of grass that was not mowed by the land owner. Most evidence of recent small mammal activity was unfortunately lost shortly before the test commenced because of mowing and burning of the slope surfaces, but the entrances to the main burrows remained relatively intact. Figure

4-4 shows the landside slope prior to excavation, indicating the location of burrows and one of the sandbag rings shown on Figure 4-2d.

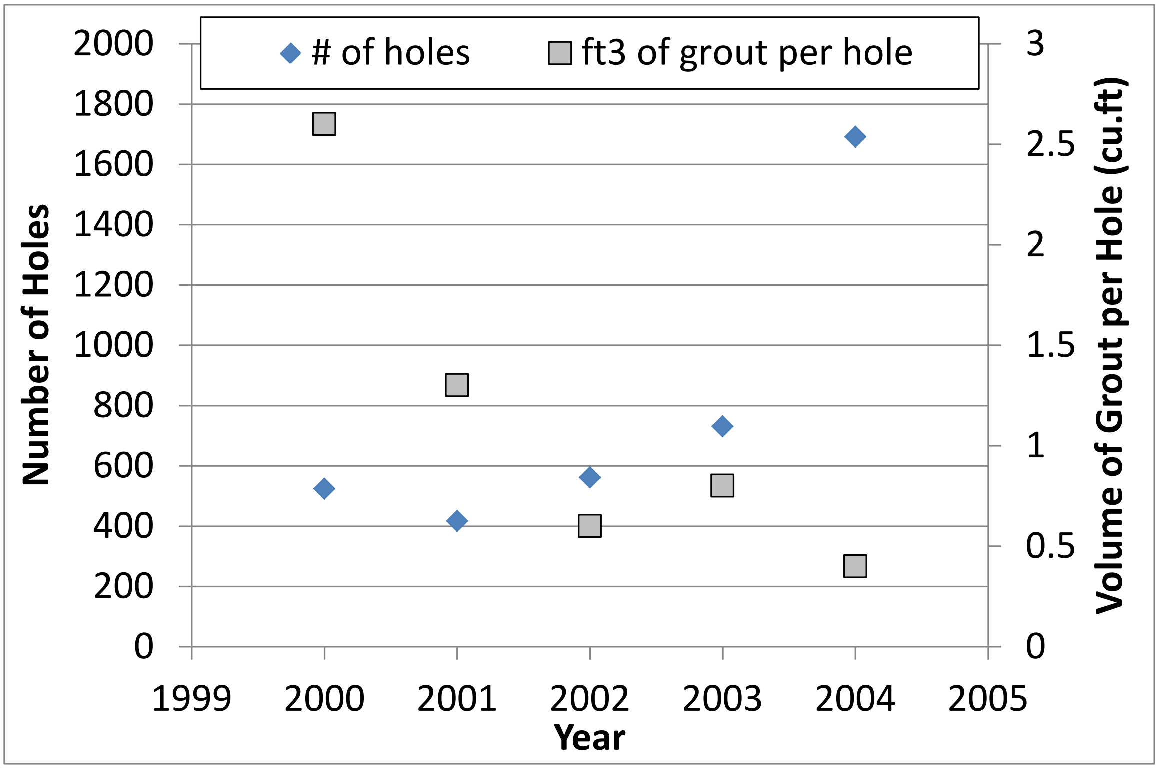

Figure 4-3. Volume of grout used on the clayey levee site from 1995 to 2004 (data provided by Al Romero, DWR)

Similar types of intrusions were observed on the waterside slope, with most burrows concentrated on the upper half of the slope (Figure 4-5). In contrast with the sandy levee site, the few remaining ejected soil 'porches' were composed of chunks of clay and few gravel particles, representative of the material composing the levee embankment. Surveying activities were performed in similar fashion as described for the sandy levee, but differentiation of active and inactive holes was more challenging on this site because of the previously mentioned mowing and burning. A plan view of identified burrows is shown on Figure 4-6. Twelve active California ground squirrel burrows were encountered along the 20-meter long test section; fifty-two unidentified burrows were logged on the waterside slope, and seventy such holes on the landside. Based on conversations with Dr. Dirk Van Vuren of UC Davis, most of these small unidentified holes were classified as Pocket gopher holes. The urethane grout injection plan (Figure 4-7) included seventy-five ports distributed in a grid pattern and spaced at 1.2 meters (four feet).

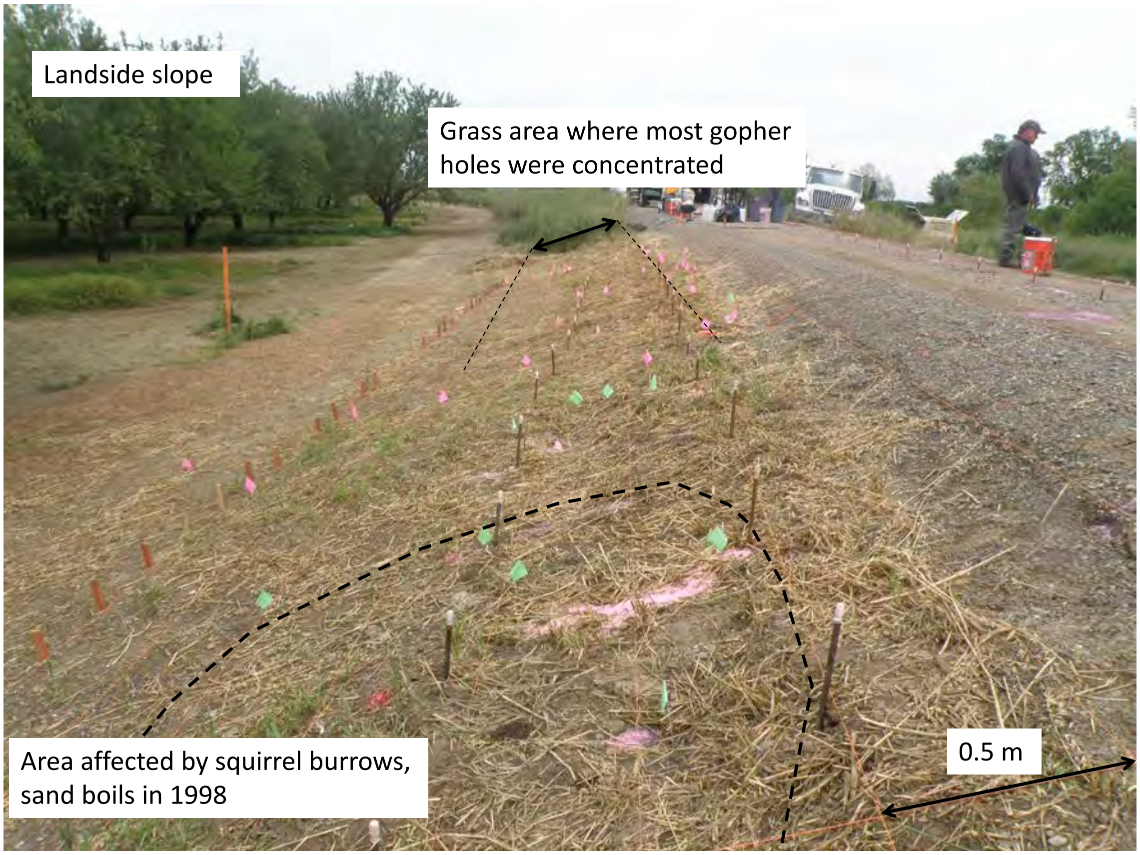

Figure 4-4. Location of burrows on landside slope of the clayey levee. Pink flagging indicates location of undifferentiated burrows, green flagging indicates burrows historically grouted with cement-bentonite by DWR.

Given this site was last grouted by DWR during late summer of 2011 (10 months before this study) it was deemed unnecessary to re-inject cement-bentonite grout before injection of the polyurethane based grout. Index soil properties were estimated prior to excavation from disturbed soil samples. Table 4-1 shows the summary of index properties estimated from five samples obtained at different points on the levee embankment; namely, near each toe, mid-slope and near the levee crest.

Figure 4-5. Typical California ground squirrel burrows on waterside slope of the clayey levee

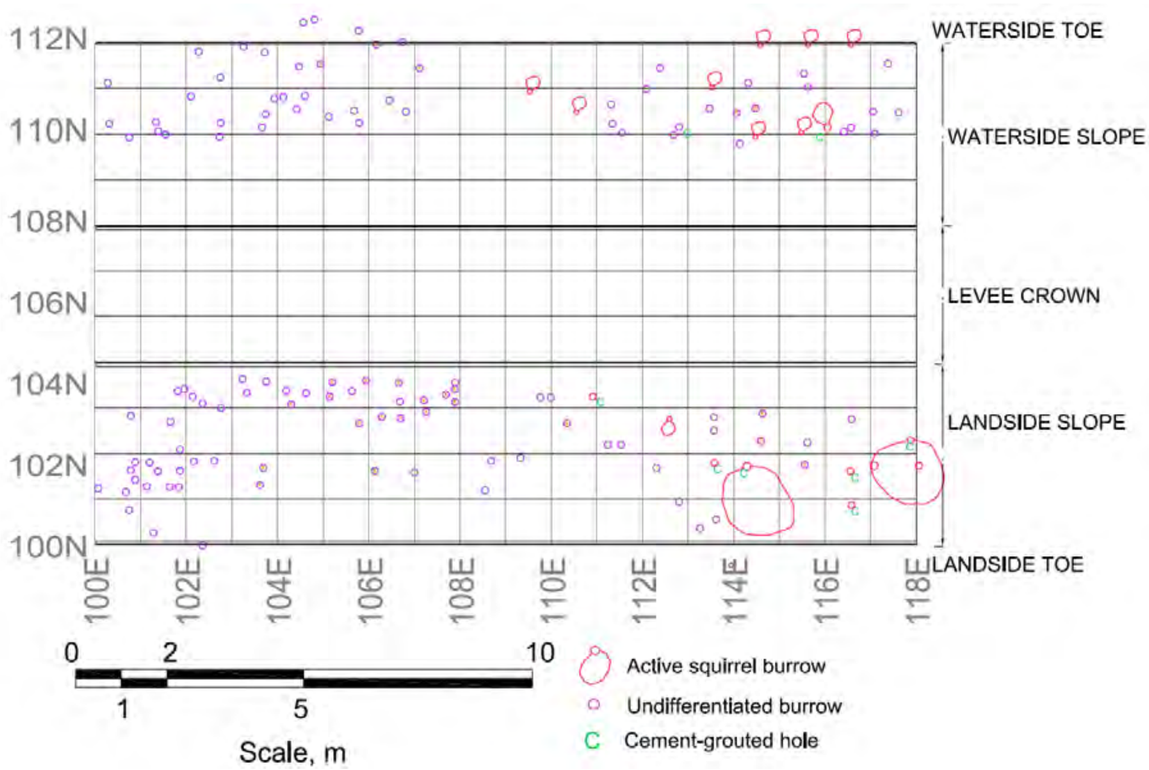

Figure 4-6. Plan view of identified burrows at the clayey levee site

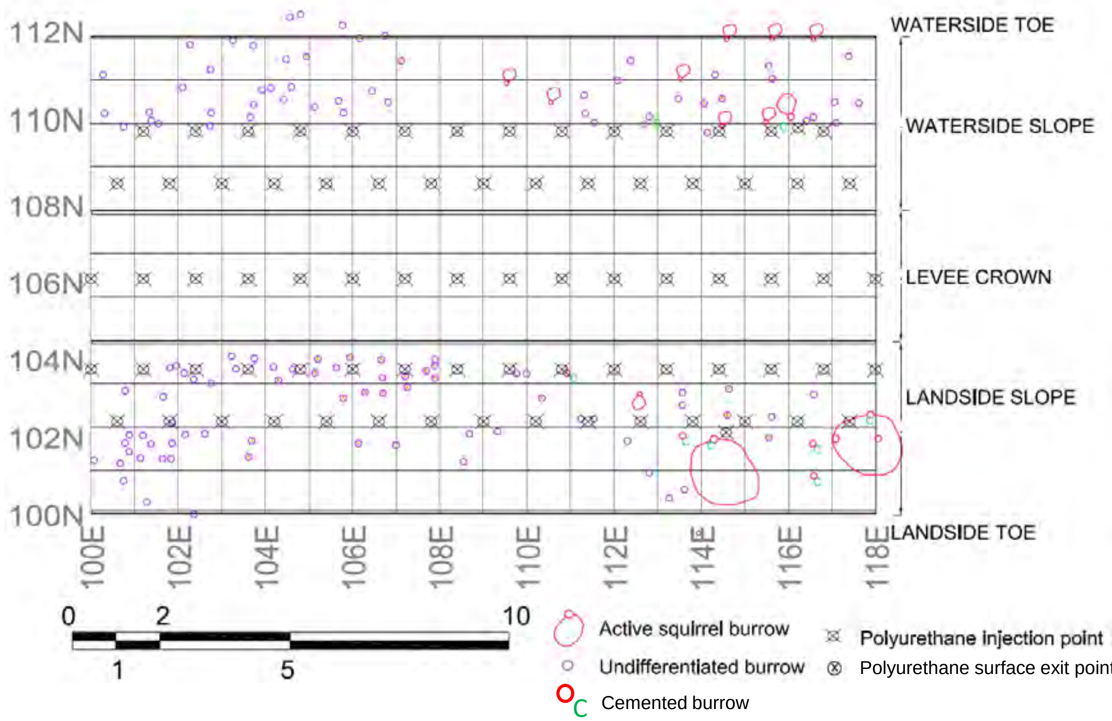

Figure 4-7. Map of grout injection points at the clayey levee site

Table 4-1. Index soil properties at the clayey levee site

Sample	% Fines	% Sand	% Gravel	LL	PI	Water Content	USCS
				(%)	(%)	(%)	
LS-1	67	30	3	-	-	35	ML
LS-2			-	-	-	39	ML
WS-1			-	-	-	41	CL-ML
WS-2			-	40	15	29	CL-ML

LS: Landside slope, WS: Waterside slope, USCS: Unified Soil Classification System, SP-SM: Poorly graded sand with silt, SM: Silty sand, ML: Silt

Based on the index tests, the material composing the embankment is clayey silt. The average moisture content at the end of the 2012 winter was 36% and average Atterberg limits were 40% and 15% for Liquid Limit and Plasticity Index, respectively. The embankment was uniform with very few sand lenses or layers. A simplified geologic cross section for the site is shown on Figure 4-8.

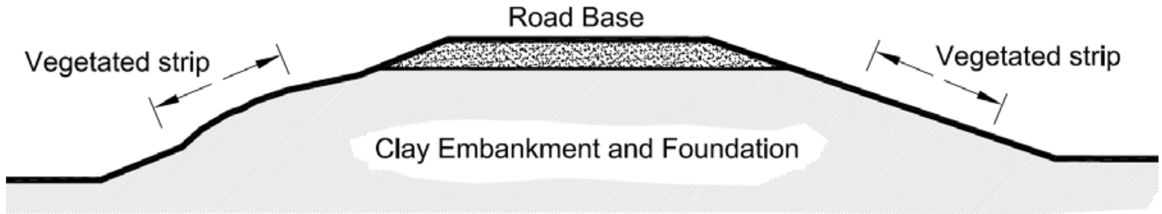

Figure 4-8. Embankment cross section of the clayey levee.

5 EXCAVATION AND SURVEYING

5.1 SITE 1: SANDY LEVEE

Excavation at the sandy levee site was performed using a combination of a compressed air powered wand, commonly known as 'air knife', hand labor and backhoe operation. The excavation started by removing approximately 50 centimeters (1.6 ft) of gravel base and compacted clay material from the top using a backhoe, and then switching to the air knife to remove thin lifts of soil, typically between 20 to 30 centimeters (0.7 to 1 ft) or until a grouted burrow was encountered, at which point the equipment was stopped and hand tools were used to carefully expose the entire burrow.

Once a grouted burrow system was exposed, the surrounding soil was removed using hand tools, the grouted burrows cleaned with paint brushes and spray-painted for easy recognition in logs, pictures and T-LiDAR scans. A bright green paint was used for all cement-bentonite grouted burrows, and polyurethane grouted burrows were colored with a pink spray paint. A small area near the landside slope was colored with orange paint because it exhibited both types of grout in comparable quantities.

A team from the US Geological Survey Sacramento office led by Dr. Gerald Bawden visited the site every day after burrows were exposed and painted, and performed T-LiDAR scans of the exposed burrow systems. A minimum of six scans were performed per day from different angles using the two devices mentioned in previous sections with the objectives of minimizing shadows in the point clouds and obtaining volumetric representations of the burrows.

The excavated material on the waterside levee slope was mostly sand and therefore the air knife was very effective in quickly removing a large portion of the slope. After exposing a large burrow near the waterside toe, no additional grouted burrows were found; therefore, the backhoe was used to remove the remaining soil along this slope. In contrast, the landside levee slope proved to be more challenging to excavate and several large burrow complexes were encountered just below a stiff silt layer located below the crown and extending to approximately mid-slope on the landside slope.

5.1.1 WATERSIDE BURROW SYSTEM

As noted above, a single large burrow was encountered on the waterside slope, approximately one meter above the levee toe. This burrow extended parallel to the toe between the two large active openings shown on Figure 3-3 and had two main arms extending into the levee. Figure 5-1 shows the initial excavation of this burrow, which extended approximately 2.5 meters in the direction parallel to the toe and was mostly filled with cement-bentonite grout between the two burlap bags indicating the cement based grout injection points, except for a 40 centimeter (1.3 ft) segment filled with polyurethane that seemed to join the ends of the cement-bentonite grout. A 1.5 meter (5 ft) urethane-filled burrow was encountered to the western end (upper left side of Figure 5-1) of this system, extending approximately normal to the levee toe alignment. Finally, the largest and more important component of this burrow system was observed near the eastern edge of the burrow (bottom right of Figure 5-1), where a large diameter burrow mainly grouted with cement extended from the burlap bag approximately 2 meters (6.6 ft) into the levee with an average diameter of 40 centimeters.

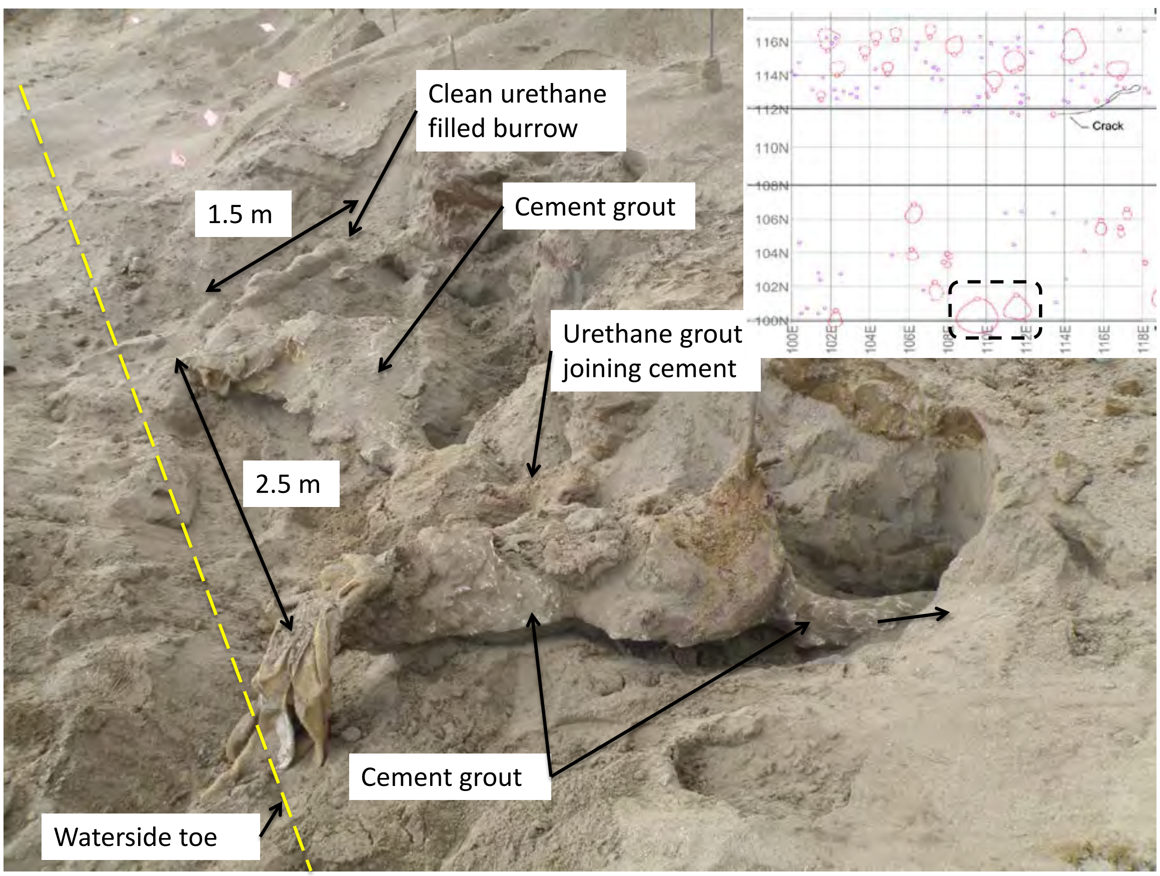

Figure 5-1. Exposed burrow system near waterside toe of the sandy levee

The diameter of the burrow decreased to approximately 20 centimeters and continued into the levee for an additional 2.4 meters (7.9 ft) (Figure 5-2) and finished in a disc-shaped den of approximately 35 centimeters in diameter and 20 centimeters in thickness. A 30 centimeter long tunnel was observed extending below the den (Figure 5-3), which could have been used as a disposal for droppings by the burrowing animal (Van Vuren, 2012).

The extent of the main burrow and den coincided with the interface between the silty material and the loose sand composing the majority of the levee, as the stiffer fine grained soil would provide a stable roof for the burrow, dug by an animal efficiently digging inside the loose sand. This observation was consistent several burrows at this site. Other burrows were observed to have been dug in the fine grained layer.

Evidence of the persistence of burrowing activities was observed during the grouting on the site: sometime during the two weeks between the end of the cement-bentonite grouting and the start of the polyurethane grouting programs, a new hole was observed between the two large active burrows near the waterside toe shown on Figure 3-3. Excavation revealed that this new hole followed the previously grouted linear burrow into the levee and likely reached the disc-shaped den; but it is unclear whether it was created as a new burrow or if it as dug was an escape route by an animal trapped in the adjacent grouted tunnel. Figure 5-4a shows the location of the new burrow entrance relative to the previously grouted large burrows, and Figure 5-4b is a close up of the 10 centimeter-diameter (0.3 ft) ungrouted new burrow below the cement grouted burrow.

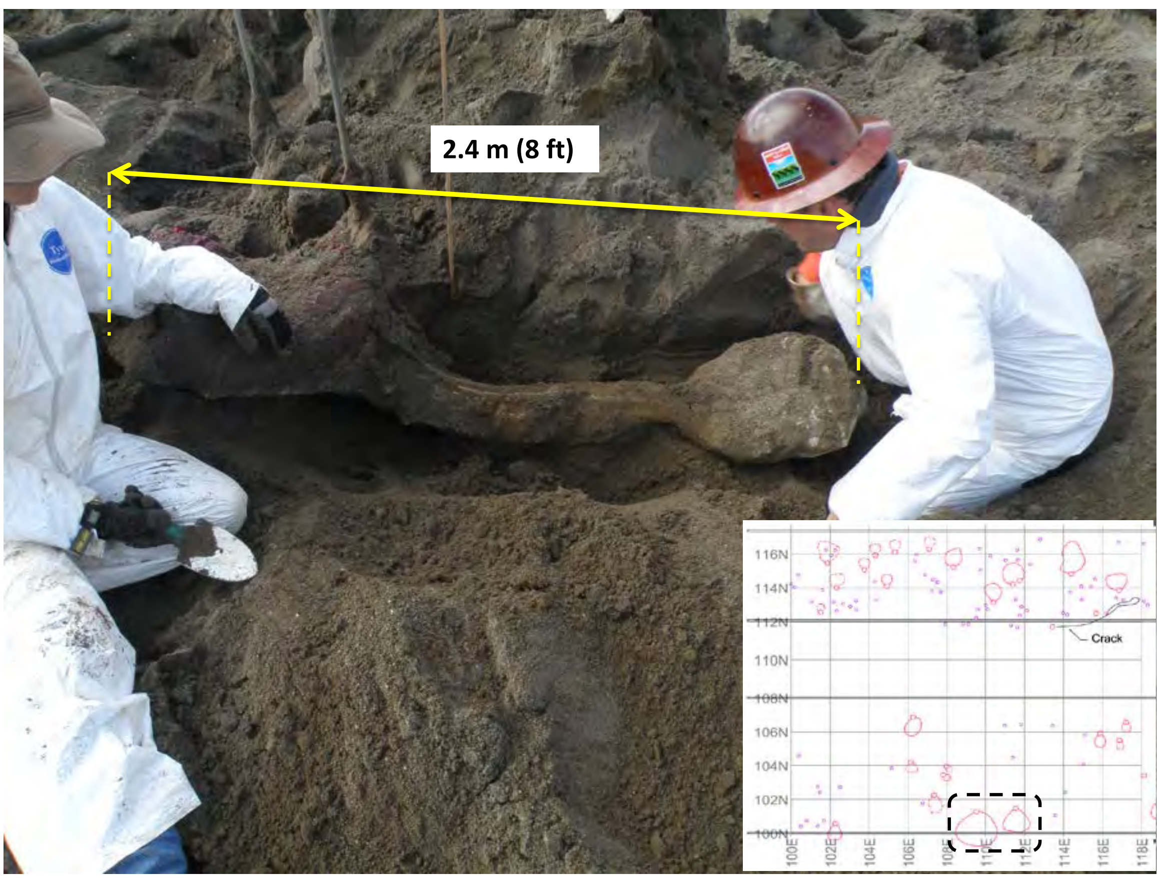

Figure 5-2. Continuation of waterside burrow into the levee on the sandy levee

The total length of the waterside burrow system was measured to be 5.2 m, and its approximate volume was 0.3 m^3 (10.5 ft^3). Approximately 70% of this volume was comprised of cement-bentonite grout, and the remaining 30% of polyurethane grout. The void left by the new burrow was not considered in these volume estimates. Additionaly, several ungrouted burrows were encountered during post-grouting excavation, these were not captured by the T-LiDAR surveys and not quantified in the volumetric estimations.

Figure 5-3. Close up of den (grout mass) near waterside toe of the sandy levee. The wooden stake points to a short burrow below the den.

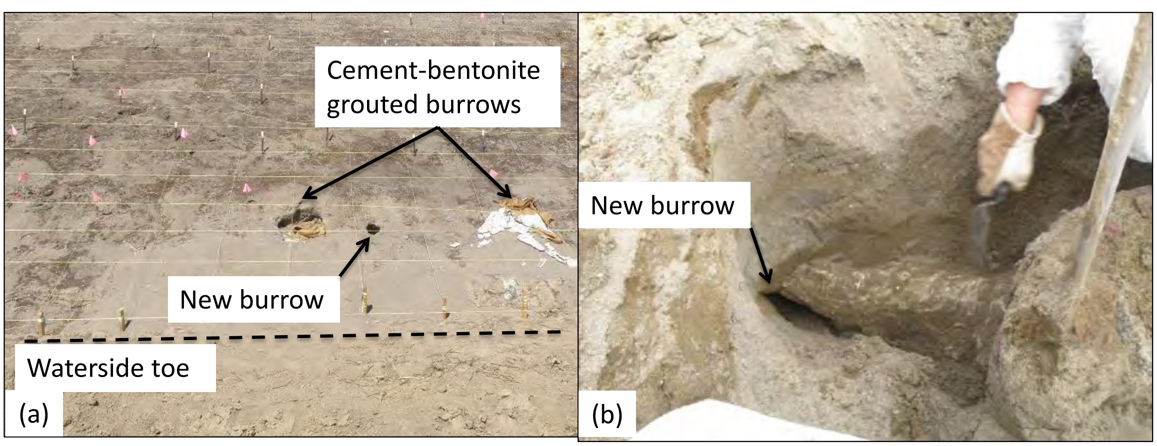

Figure 5-4. New hole after cement-bentonite grout on waterside toe of the sandy levee Site. (a) shows the location of the new burrow and (b) shows the partially excavated open burrow below the cement-grouted main tunnel.

5.1.2 LANDSIDE BURROW SYSTEM

The burrow systems encountered on the landside were longer and much more complex than the linear feature found near the waterside toe. A multi-level complex was observed from approximately one meter below the landside edge of the crown of the levee near the eastern end of the test site, and extended west for approximately ten meters parallel to the levee alignment. This complex connected all the large active burrows grouted using cement-bentonite and was measured to be 56.4 meters (178 ft) in total length and approximately 1.1 m^3 (38.8 ft^3) in volume. 75% of the estimated volume corresponded to cement-bentonite grout and the remaining 25% to polyurethane grout.

Several smaller burrows were observed away from the main complex, one near the levee toe extending for approximately two meters parallel to the levee alignment, and a second burrow was encountered west of the edge of the complex; both of these burrows were entirely grouted with polyurethane, and the latter might have been part of the main burrow complex at some point.

Figure 5-5 shows a view from the top of the eastern edge of the main burrow complex, which consisted in a series of intertwined tunnels ranging from five to fifteen centimeters in diameter occupying an area of approximately 2.5 meters (8.2 ft) in the direction parallel to the slope (left to right of photo) and 1.7 meters (5.5 ft) in the normal direction. This area contains the largest volume of grout in the study and coincides with cement-bentonite injection point number 4 in Table 3-1, which took approximately 25 minutes to fill.

The colored grout on Figure 5-5 indicates a large portion of the complex was filled with cement-bentonite grout (green color), and several large pieces were filled by the polyurethane grout (pink color). Several additional polyurethane injection ports were installed in this area with the objective of effectively filling all voids; however, some of these ports were inadvertently pushed through the already hardened cement-bentonite grout, causing it to break and allowing polyurethane to flow through the cracks and generate a mixed grout area, colored with orange spray paint (right edge of burrow complex).

The burrow complex extended upstream (top of Figure 5-6) and divided into two main tunnels of approximately 15 centimeters (0.5 ft) in diameter; the alignment of these tunnels dipped down approximately 50 centimeters (1.6 ft) and converged into a single tunnel that sharply increased in elevation at the end of the burrow system. Figure 5-7 shows a lateral view of the landside burrow complex at the end of the excavation activities, at which point the main intertwined portion (Figure 5-5) had been removed to expose deeper portions of the system.

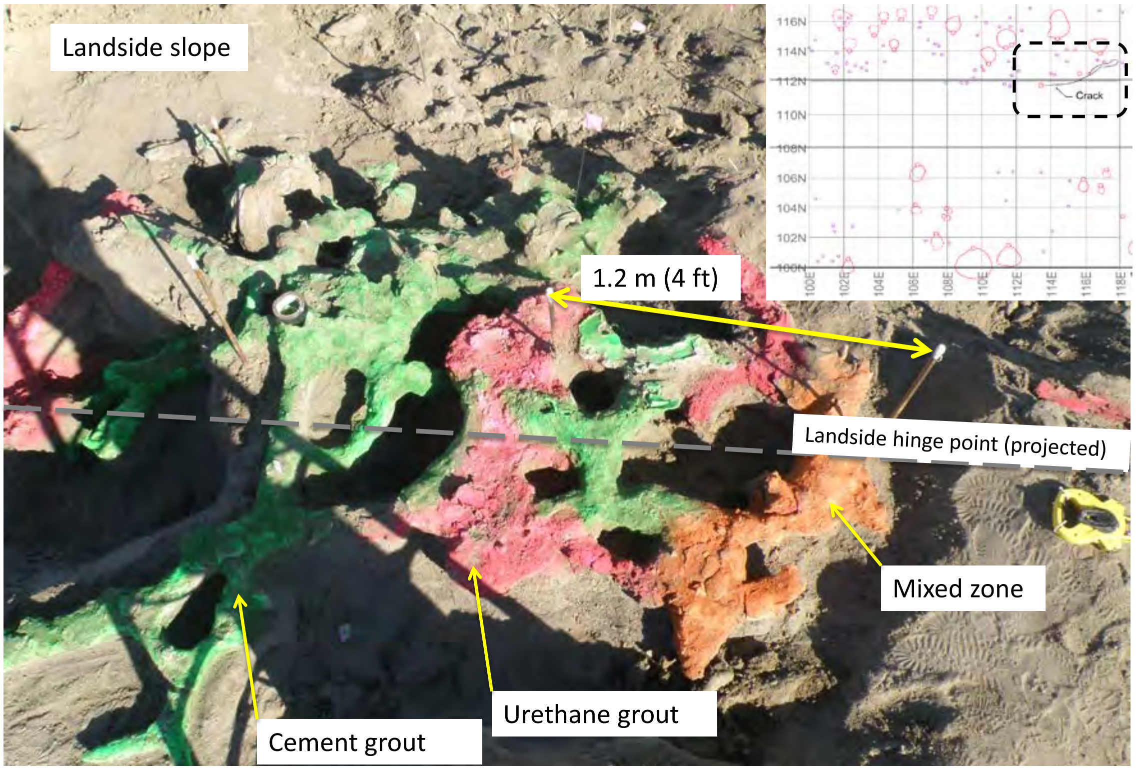

Figure 5-5. Aerial view of east edge of main complex near landside edge of crown

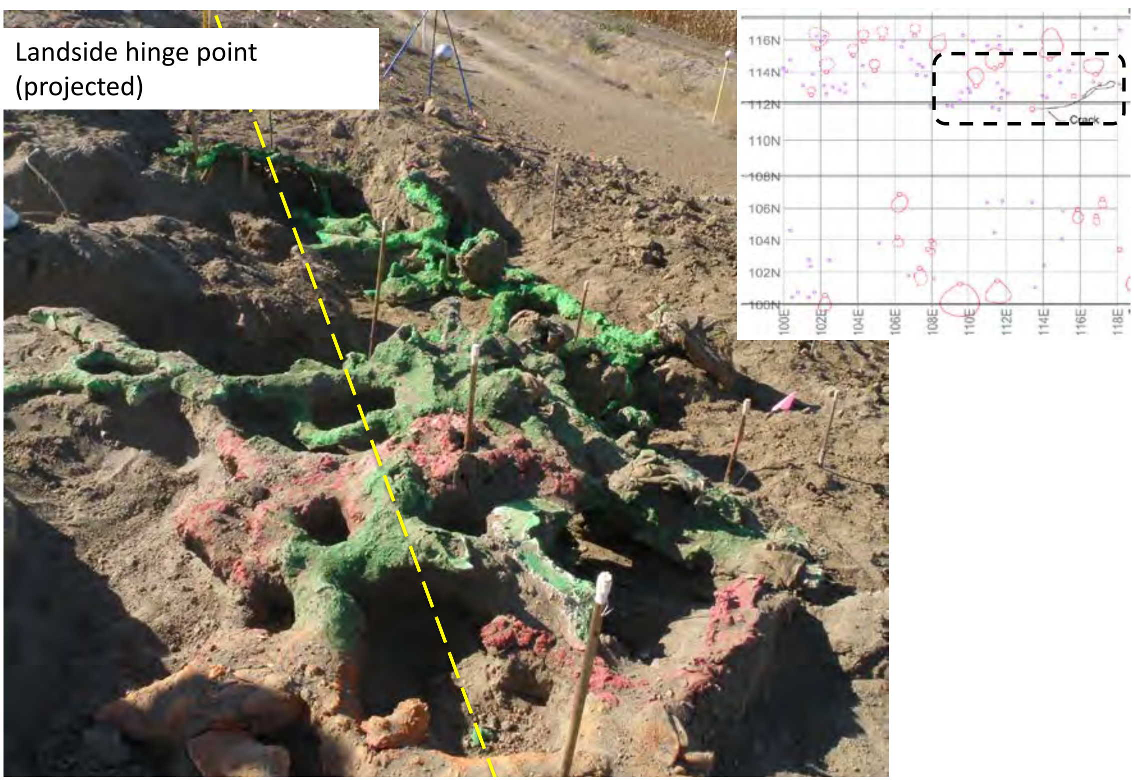

Figure 5-6. Oblique view looking upstream of main complex near landside edge of crown

The perspective shown in Figure 5-7 allows defining three distinct levels of the landside burrow system: (1) the shallowest portion of the complex coincides with the very dense and intertwined zone previously described, which connected all the cement-bentonite grout injection points; (2) a deeper level, where the system of burrows is composed by two main tunnels, and (3) a single tunnel that sharply rises to an elevation similar to level 1. An isolated burrow grouted exclusively with polyurethane was observed near the landside toe (bottom of Figure 5-7); approximately 1.5 meters (4.9 ft) below level 2 of the main complex and extended 2 meters (6.6 ft) parallel to the levee alignment, with a sharp turn towards the interior of the levee.

T-LiDAR data collected by USGS was processed using the program IMVIEW, allowing the differentiation of the different types of grout and consequently estimating lengths and volumes. For estimation of grout volumes, individual burrow segments were exported as point clouds to AutoCAD, and a three-dimensional surface was fitted along the points on the surface of the burrow. Figure 5-8 shows a cross sectional view of the LiDAR data, with the waterside slope to the right of the figure. This image allows visualizing the extension of the landside burrow system from the toe to essentially the centerline of the embankment. Figure 5-9 and Figure 5-10 contain close-ups of the landside and waterside burrow systems, respectively.

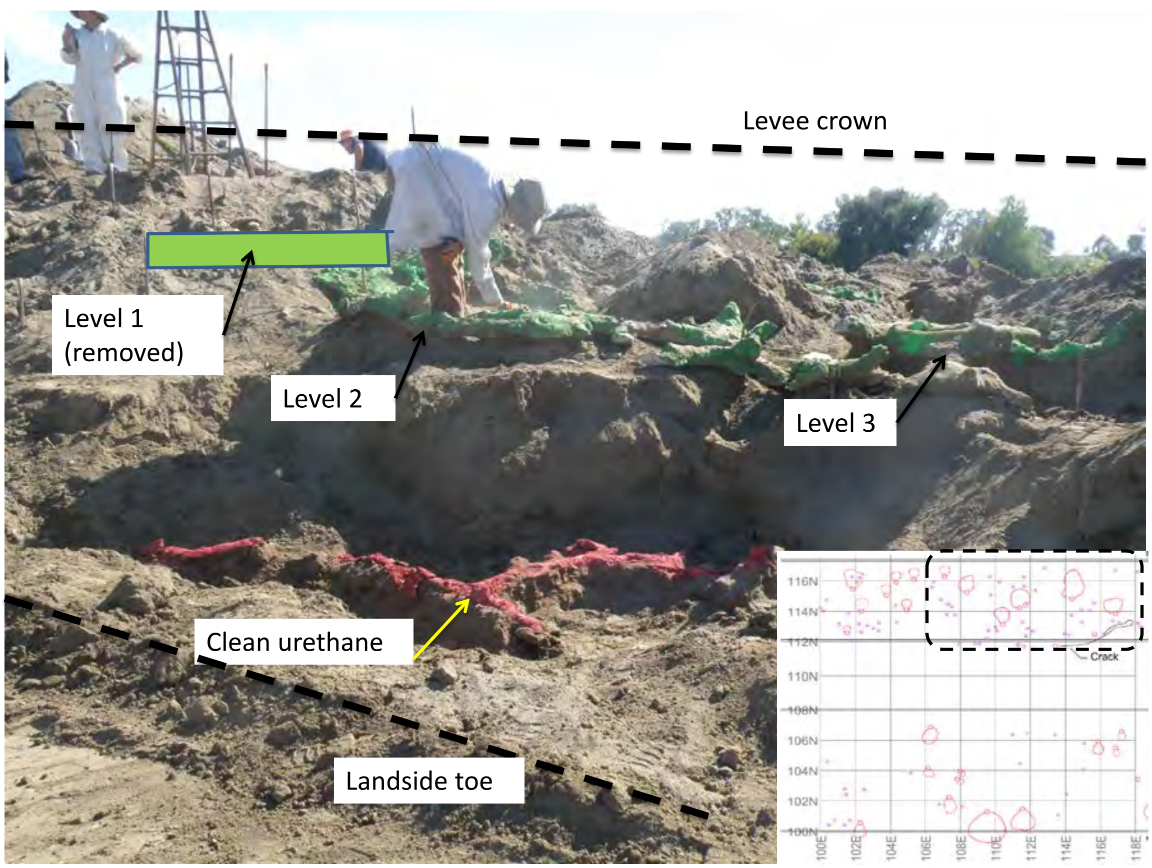

Figure 5-7. Lateral view of landside levee slope burrow system

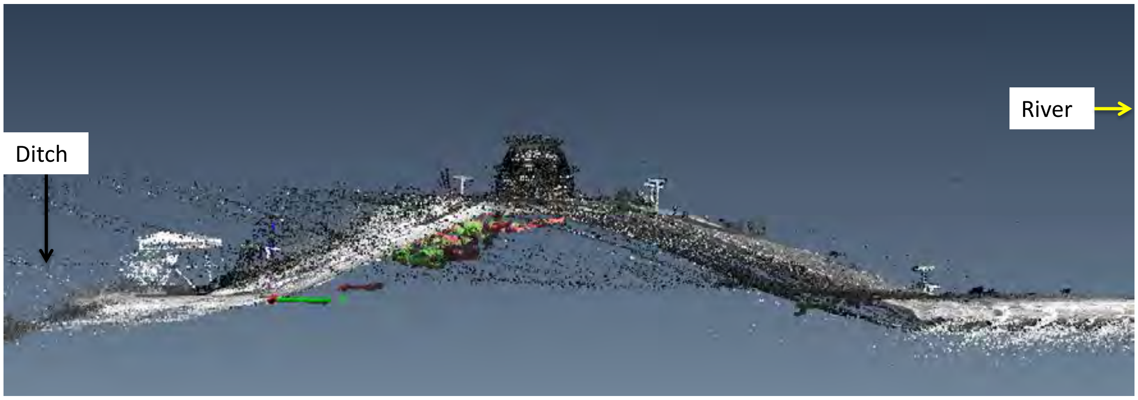

Figure 5-8. Cross section showing LiDAR data on the sandy levee

The figures below give testament to how intricate and large burrow systems can become if no grouting (or void filling) or species control is performed on a levee. The surveyed burrows extend for several meters in all directions, and even though a burrow extending from one side of the levee to the other was not encountered, the potential for wetting front instability and rapid saturation is clear given the large volume of voids generated within the embankment.

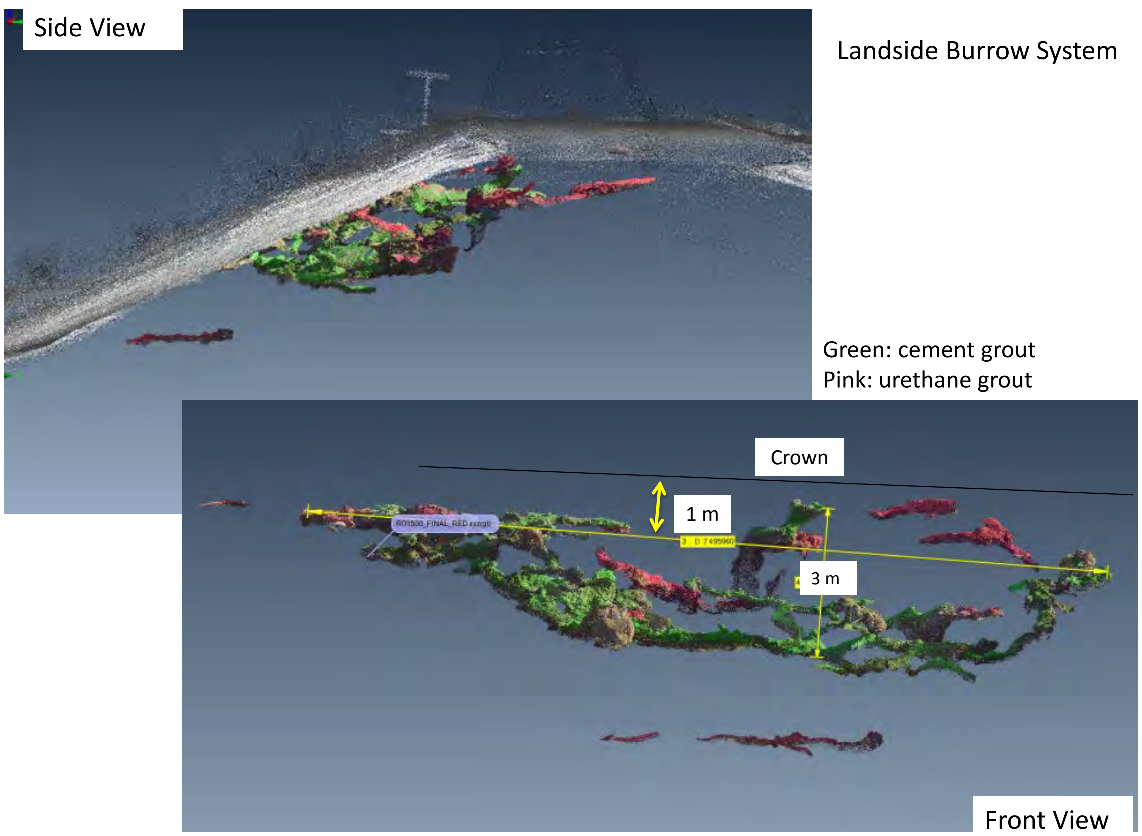

Figure 5-9. Close-up of landside burrow system (a) shows a cross section view, (b) a front view [1 m: 3.28 ft]

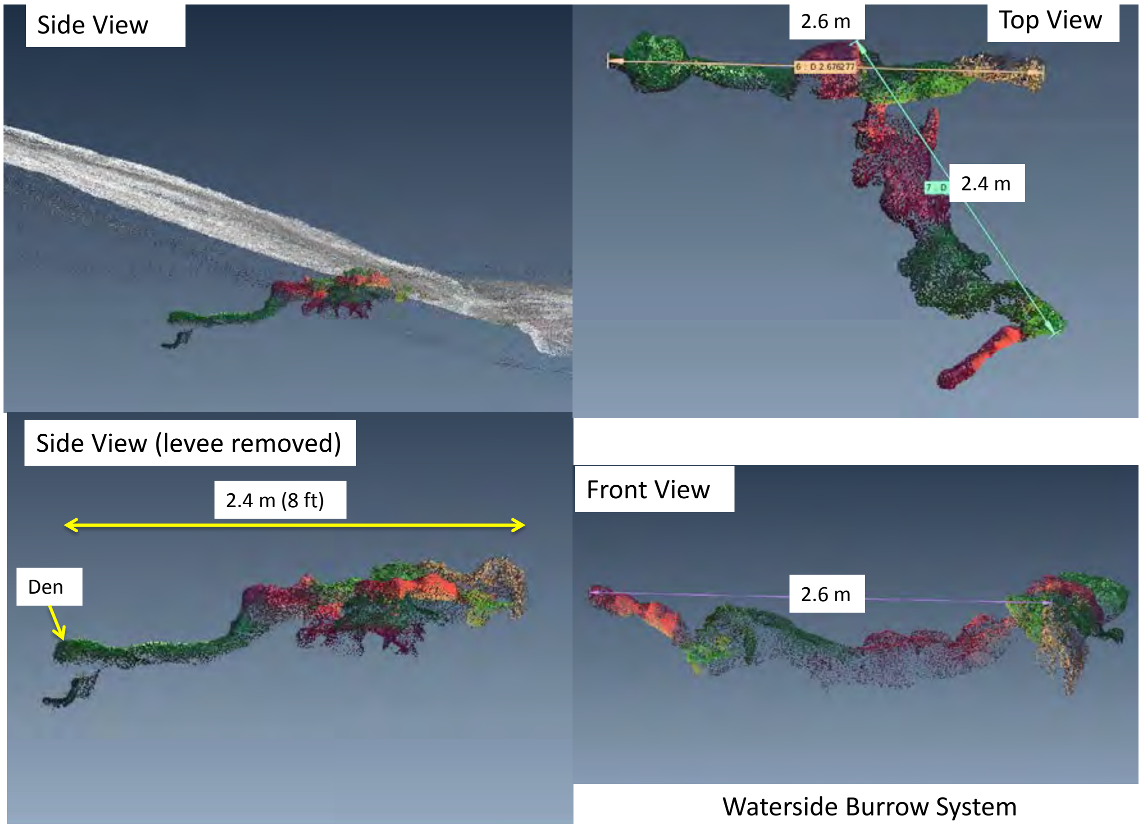

Figure 5-10. Views of the waterside burrow system. [1 m: 3.28 ft]

5.2 SITE 2: CLAYEY LEVEE

5.2.1 LANDSIDE BURROW SYSTEM

The burrow system encountered on the landside slope was similar to that on the Sandy Levee Site, with intricate and interconnected multi-level systems created by California ground squirrels and Pocket gophers. Most of the burrows coincided with a strip of grass (Figure 4-8) that is not mowed by the adjacent landowner, making it a food source for the pocket gophers. California ground squirrels, on the other hand, created larger burrows (10-15 cm in diameter) extending landward from the strip of grass toward the levee toes.

The majority of the burrows were found approximately 0.5 to 1.0 meters (1.6 to 3.3 ft) below the surface of the slope and crown, and only a few isolated burrows extended landward into the toe area, as shown on the right hand side of Figure 5-11. A single burrow was encountered extending from the waterside toward the landside slope (Figure 5-12 and Figure 5-13), approximately one meter below the elevation of the crown. This burrow was approximately 12 to 15 cm in diameter, and was grouted with cement-bentonite grout during a previous maintenance campaign. The grout was observed broken up and relatively friable, suggesting that the grout filling this hole belongs to early practices, when DWR used a higher percentage of bentonite (about 10%), which made the mix friable upon drying (DWR, 2012). The location of this penetrating burrow on Figure 5-12 coincides with one of the flood fight sites from 1998.

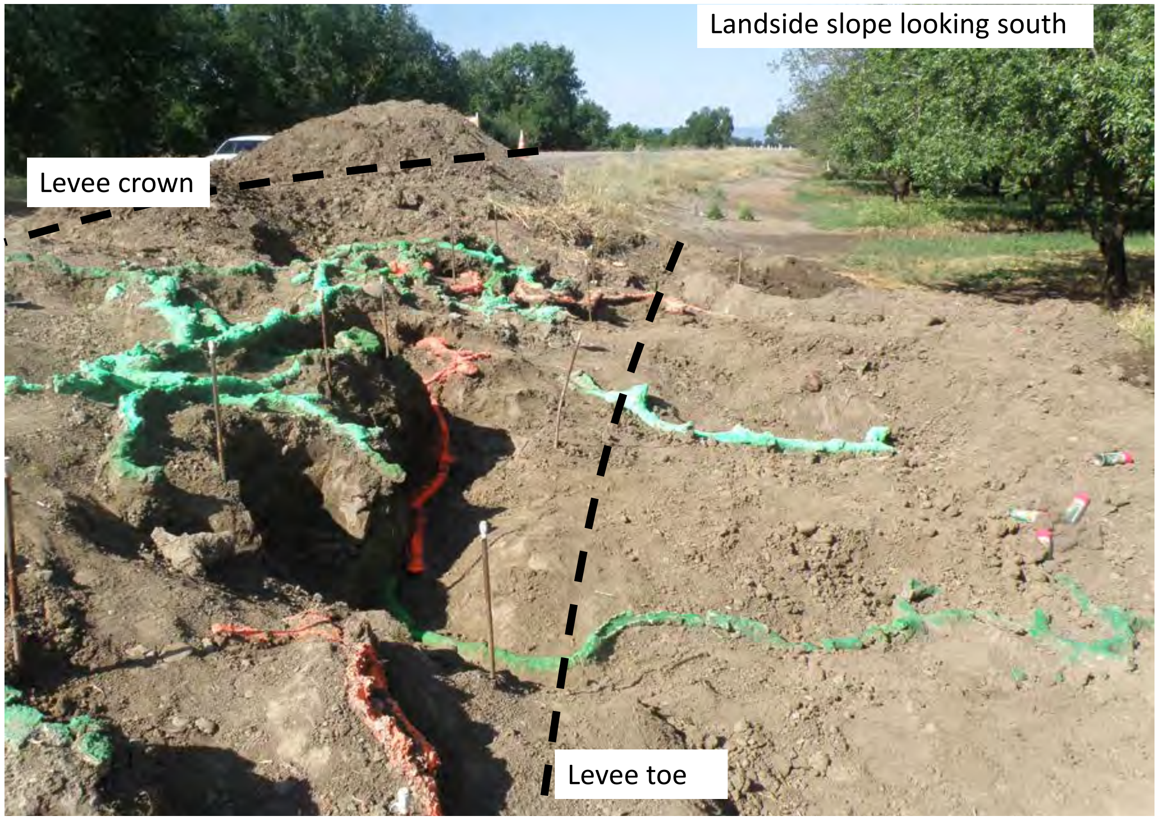

Figure 5-11. View of excavated landside slope on the clayey levee.

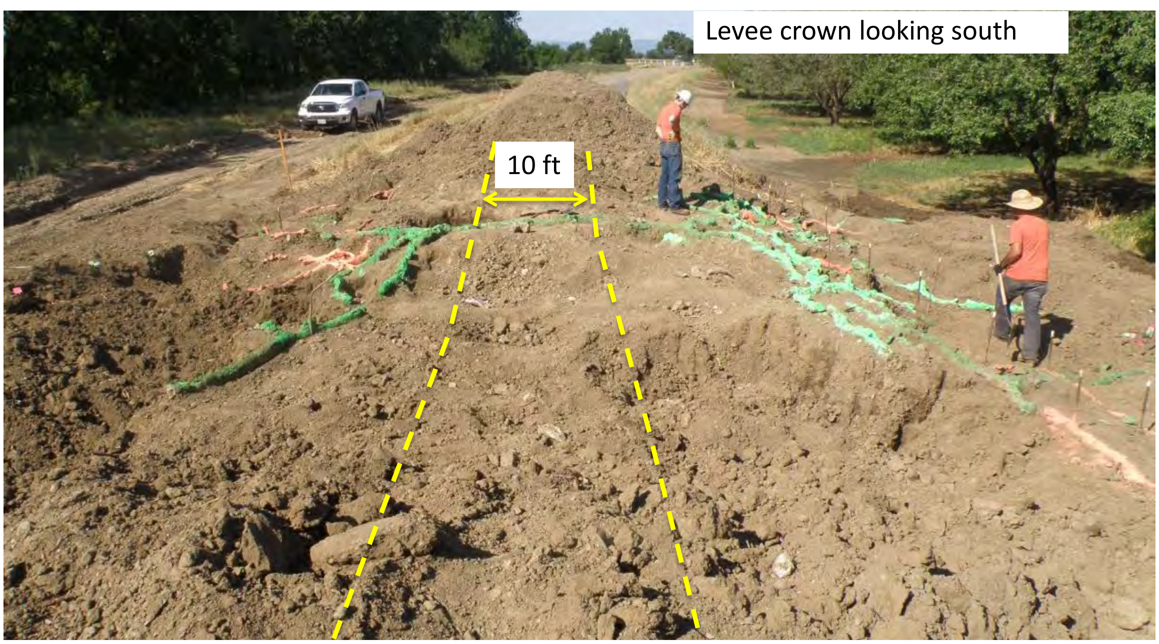

Figure 5-12. View of completely penetrating burrow

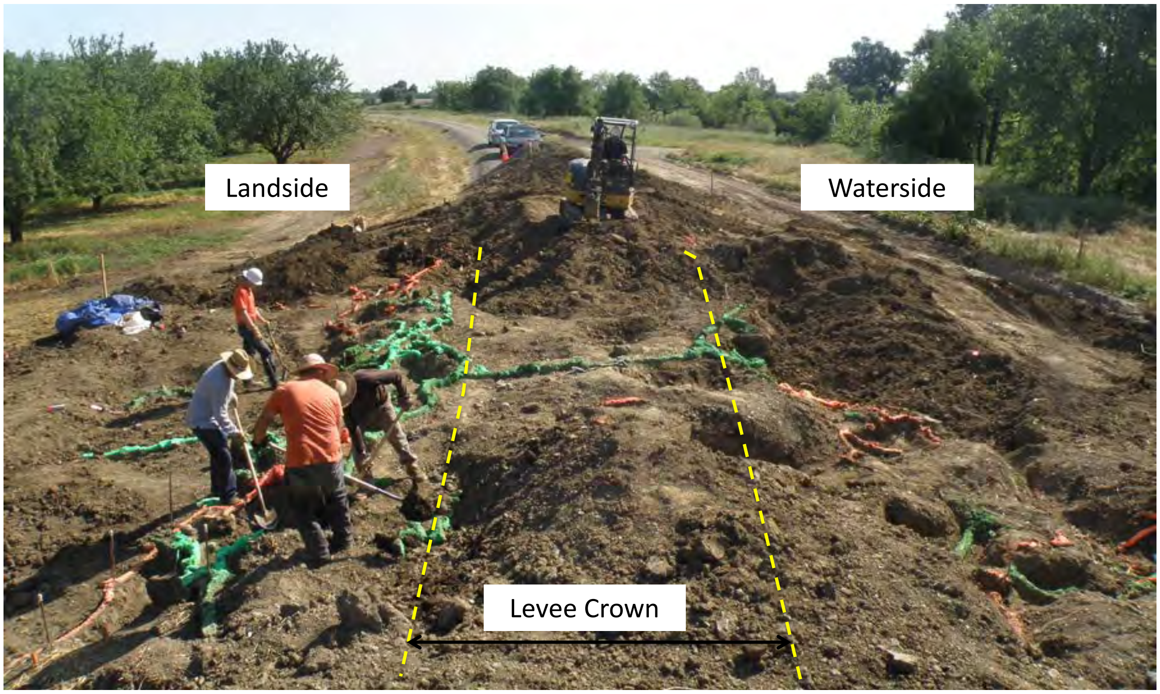

Figure 5-13. View looking north of completely penetrating burrow

5.2.2 WATERSIDE SYSTEM

The waterside levee burrow system (Figure 5-14) was not as extensive as the landside and was comprised of a few isolated burrows, mostly filled with polyurethane grout. This trend is consistent with the observations from the sandy levee, where the majority of the burrows were encountered on the landside levee slope, which coincides with the slope nearest to the food source.

The waterside 'edge' of the completely penetrating burrow was encountered approximately 1 to 1.2 m (3.3 to 4 ft) below the levee crown, and it connected to a series of short burrows also filled with cement-bentonite grout.

Figure 5-14. Oblique view of waterside burrow system

6 SIGNIFICANCE OF THE COMPLETELY PENETRATING BURROW

The results of numerical simulations to assess the influence of animal burrows on the seepage performance of embankments, from the point of view of wetting front instability and soil piping are presented in Volume 5 of this report. Piping, which is considered an important threat to levee safety, is highly dependent on three factors: (1) flow through the porous media around the pipe, (2) length and size of the pipe, and (3) particle stability. The fact that animal burrowing has the capacity to create completely penetrating burrows eliminates the variable of flow through the porous media, since the full hydraulic heads from the riverside are encountered along the entire cavity with minimal energy loss, and piping potential becomes simply a function of flow velocity inside the pipe, which in turn is dependent on the head differential between the water surface on the riverside and the entrance to the pipe. Figure 6-1 and Figure 6-2 show a cross section and plan views of the completely penetrating hole and burrow system for the Clayey Levee Site. The penetrating burrow was encountered approximately one meter below the top of the levee, almost perpendicular to the levee alignment.

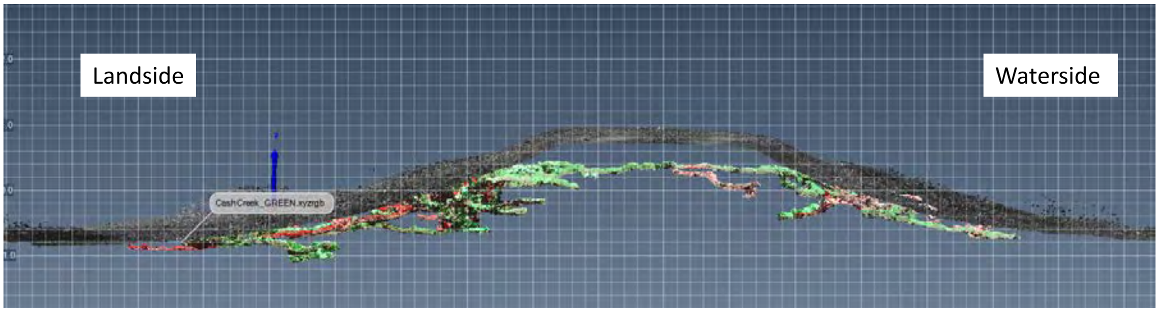

Figure 6-1. Cross section view of completely penetrating burrow through the clayey levee

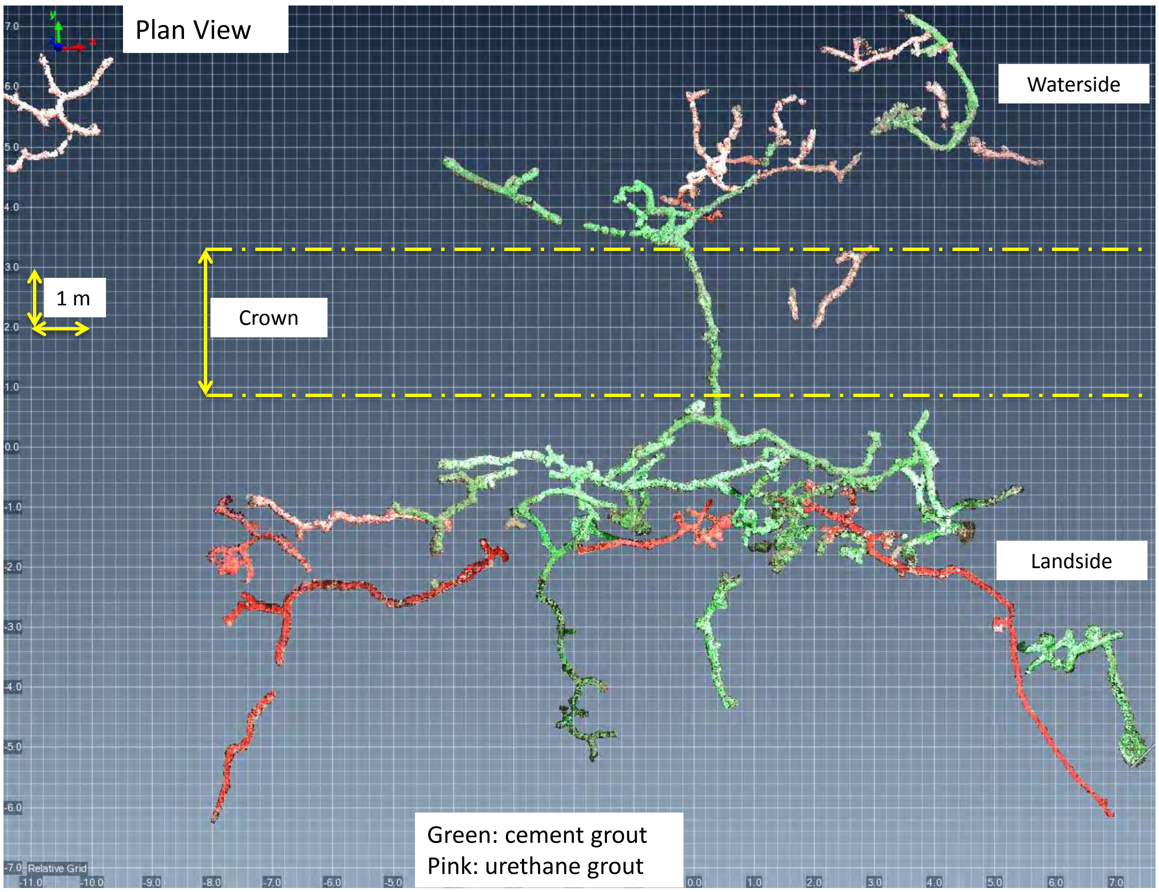

Figure 6-2. Plan view of burrow system in the clayey levee

7 SUMMARY OF RESULTS AND OBSERVATIONS

The burrowing activities by the California ground squirrel on the sandy levee site were found to be very strongly correlated with proximity to a food source very near the landside levee toe, as evidenced by the amount of active and inactive burrows on the landside slope as compared to the waterside slope. This was observed not only for the 20 meter (60 ft) long study site, but along the entire stretch of this levee adjacent to a large corn plantation. The number of burrows on this surface was twice the number observed on the waterside slope, and the volume of voids created by the burrowing activities over the years was significantly larger on the landside (1.0 to 0.3 m^3).

Layering and soil type was also observed to have a strong influence on the amount and extent of burrowing on the sandy levee. Figure 7-1 shows two instances where the burrows follow an interface between a stiff fine-grained or cemented sand layer overlying the loose sand material composing most of the embankment, most likely because the animals prefer to dig through the loose materials, while at the same time having a stiff and stable roof. This was the case for most of the burrows observed on the sandy levee as well as other sandy levees. Several other burrows were encountered exclusively along the stiff fine-grained layers in the levee embankment. Similarly, Harder et al (2012) investigated root penetrations into a slurry wall and found a ground squirrel burrow penetrating the slurry wall from the crown of the levee and extending several feet below the crown along the interface of the slurry wall and surrounding sandy embankment.

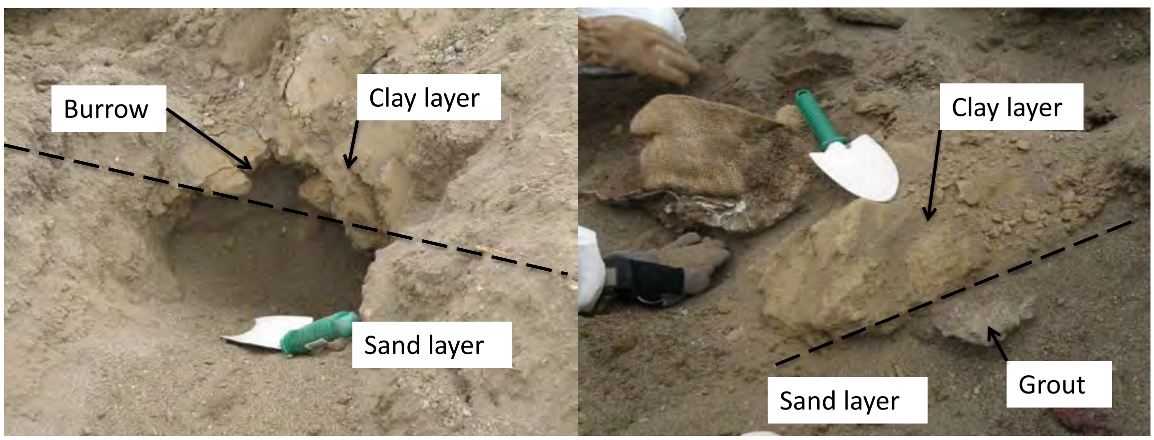

Figure 7-1. Layer interface facilitating burrowing in the sandy levee.

Another key observation from the sandy levee site is the persistence of burrowing activities; as shown on Figure 5-4, a new burrow was dug between the two large burrows near the waterside toe after the cement-bentonite grout was injected, and followed the alignment of the grouted burrow. Furthermore, during a field visit several months after the test was completed and the levee had been rebuilt, new burrows were observed within the repaired levee section (Figure 7-2) and on the landside berm.

Despite the relatively large amount of cement-bentonite and polyurethane grout injected into the embankments, several ungrouted burrows were encountered during excavation of both sites, especially on the sandy levee site, which, as discussed earlier, does not have a regular grouting program in place by the reclamation district. Figure 7-3 shows two ungrouted burrows encountered during excavation. These once again coincided with the interface between a stiff fine-grained layer and the sandy embankment (Figure 7-3a) and the contact between the compacted road base and underlying levee material (Figure 7-3b).

Figure 7-2. New burrows on landside slope of the reconstructed sandy levee

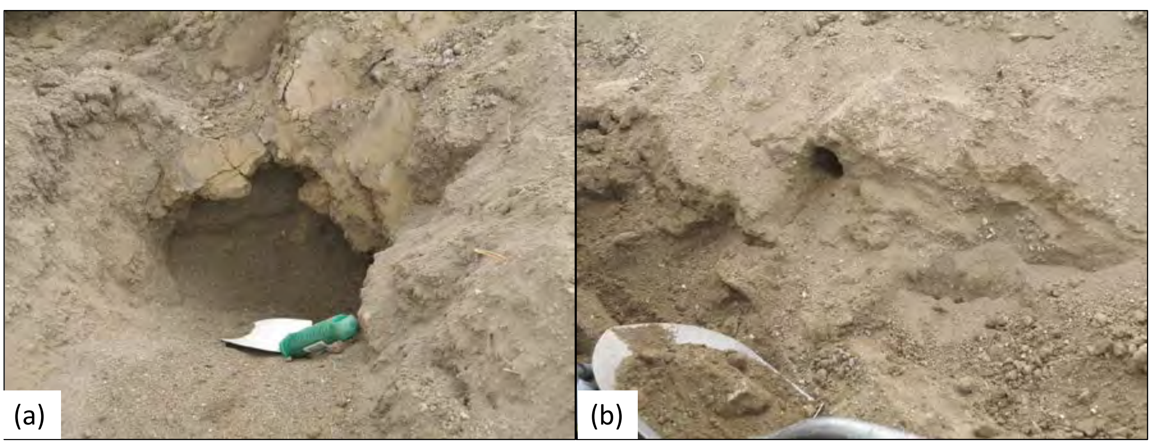

Figure 7-3. Ungrouted burrows in the sandy levee: (a) A burrow near Level 1 of the large landside burrow complex, and (b) An ungrouted burrow to the west of the same complex

Similar conclusions can be drawn from the observations at the Clayey Levee site. The main difference between the two tests was that this site had history of piping and, therefore, is regularly grouted, but despite these efforts, approximately 20% of the holes created by burrowing mammals had not been grouted. The percentages of cement to polyurethane grouts are similar to those at the sandy site (80 to 20%), yet the volume is slightly smaller given that the clayey levee prism is also smaller.

8 EFFECTIVENESS OF THE CEMENT-BENTONITE GROUT

The effectiveness of the current DWR grouting practices was studied by quantifying the volume of grouted burrows using this technique, and comparing it to the total volume of burrows documented in the field program. The estimates are given below (Table 8-1) differentiating the two test sites.

Table 8-1. Summary of grout volumes

	STUDY SITE	
	Sandy Levee	**Clayey Levee**
Cement-Bentonite Grout, m3	1.02	0.96
Urethane Grout, m3	0.37	0.21
Total Volume, m3	1.39	1.17
% Cement-Bentonite	74%	82%
% Urethane	26%	18%
% of Levee Soil Removed by Burrowing Activity[1]	0.24%	0.31%

[1]Calculated as percentage of the total volume of levee soil in the test section. [1 m^3: 35.3 ft^3]

Current DWR grouting practices were successful in filling between 70 and 80% of the existing burrows at the two test sites. While the two sites were widely different in terms of levee material and maintenance practices, there are similarities that point to the effectiveness of the cement-bentonite grout treatment, as well as some of its shortcomings.

Most of the large, open burrows were effectively grouted with cement-bentonite and most of these burrows appear to be connected, forming large complex burrow systems. Complete filling of these systems is a difficult task due to the viscosity of the fluid. Several instances of partially filled holes with voids within the hardened grout were observed in both sites. Also, maintenance crews limit grouting efforts to large (10 cm diameter or larger) open burrows, leaving potentially large holes ungrouted, if their entrances were collapsed prior to grouting.

The total volume of cement-bentonite grout was 8% larger for the site with regular maintenance, which at first glance may not appear to be a significant difference to warrant yearly grouting. However, the data on Figure 4-3 suggests that through the implementation of a regular, ongoing grouting program the amount of cement bentonite grout needed to fill burrows decreases over time, which would correspond to reduced maintenance effort and reductions in yearly materials and manpower costs over time. Moreover, the site with no regular grouting program was observed to have significantly larger open burrow networks, which could lead to the seepage and stability problems described in Volume 1 of this report.

An important unknown is the long-term performance and effects of groutingon seepage and stability of a levee. After decades of injecting grout into levees, the conditions of the embankments will surely change as the levee material is replaced by grout.

Overall, current cement-bentonite injection practices prove a useful tool in grouting most of the large active burrows on a levee, as long as regular maintenance is performed. However, there is always a possibility that large holes are missed and these holes may completely penetrate a levee embankment. Thus, grouting activities have to be supplemented by regular patrolling and generation of activity databases for maximum benefit.

9 REFERENCES

Cobos-Roa, D., Shriro, M., Sitar, N., Bray, J.D., Bawden, G., Lichter, J., and Evans, R., 2012, 3-D Stratigraphy and Root Geometry From Trench and Ground-Based LiDAR Mapping, American Society of Civil Engineers GeoCongress 2012, Oakland, CA, March.

DWR, 2009, Internal Technical Memorandum, Assessment of Animal Burrow Hole Persistence on Project Levees, October.

DWR, 2012, Personal communications with field personnel during CLVRP animal burrow testing program. Harder, L., Kroll, R., Buck, P., Inamine, M., Berry, A., 2012, Investigation of Tree Root Penetration into a Levee Soil-Bentonite Slurry Cutoff Wall – Part II, 2012 Levee Vegetation Symposium, Sacramento, CA.

Van Vuren, D., 2011, Habitat Associations of Burrowing Mammals along Levees in the Sacramento Valley, California, report to California Levee Vegetation Research Program, September.

Van Vuren, D., 2012, Personal communications as part of collaborations during the California Levee Vegetation Research Program.

Appendix 4-A

ANIMAL BURROW FIELD TESTS - PHOTOGRAPHIC RECORD

Photo 4A-1. View of test area waterside slope on the sandy levee. Grid spacing 0.5 m. Large mounds of sand near the lower corner of the grid are two active ground squirrel burrows.

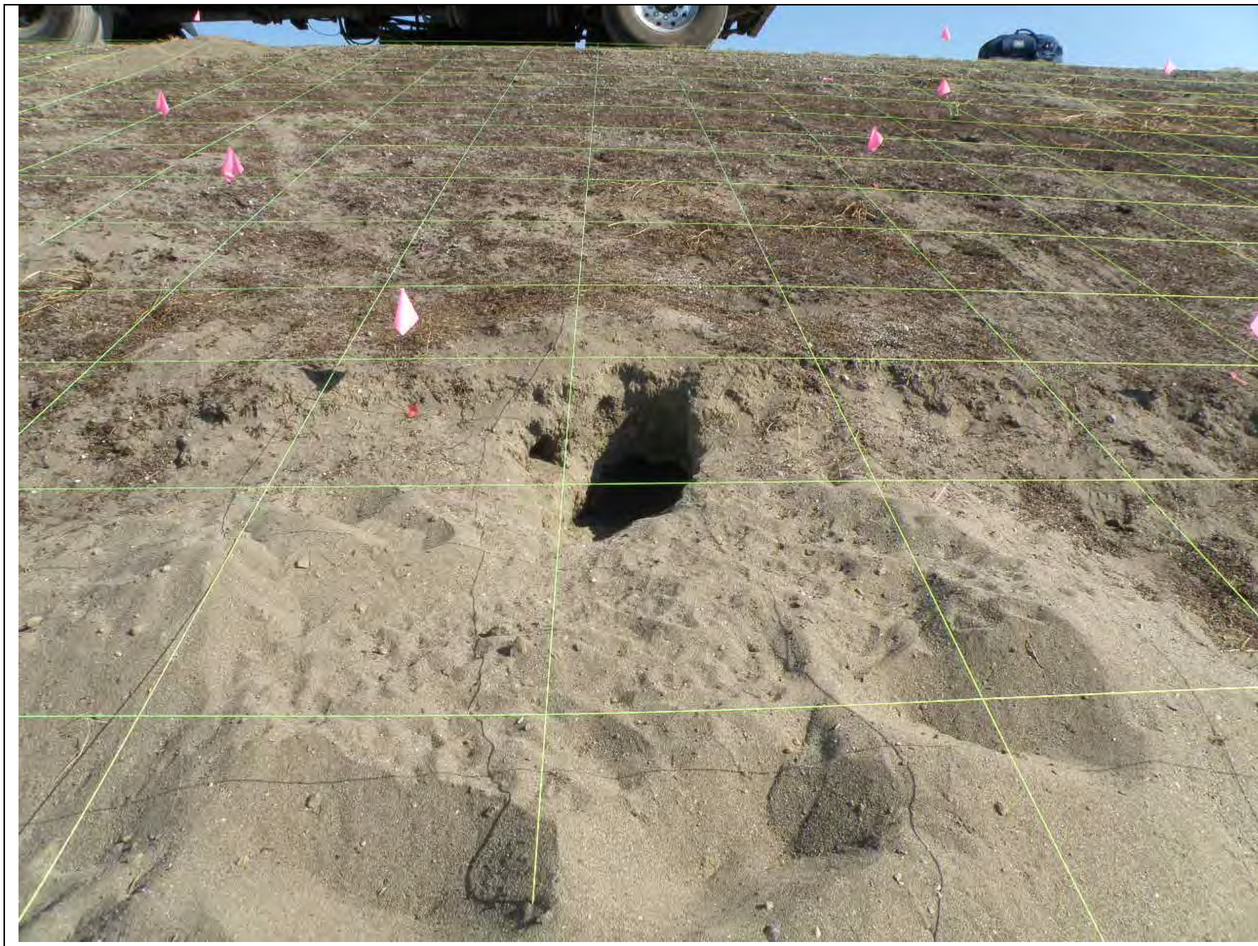

Photo 4A-2. Close up of large active ground squirrel burrow near waterside toe of the sandy levee. Grid spacing 0.5 m. Small footprints can be observed on the ejected sand cone, suggesting recent activity of the burrow.
Pink flags represent other burrows surveyed on the slope surface.

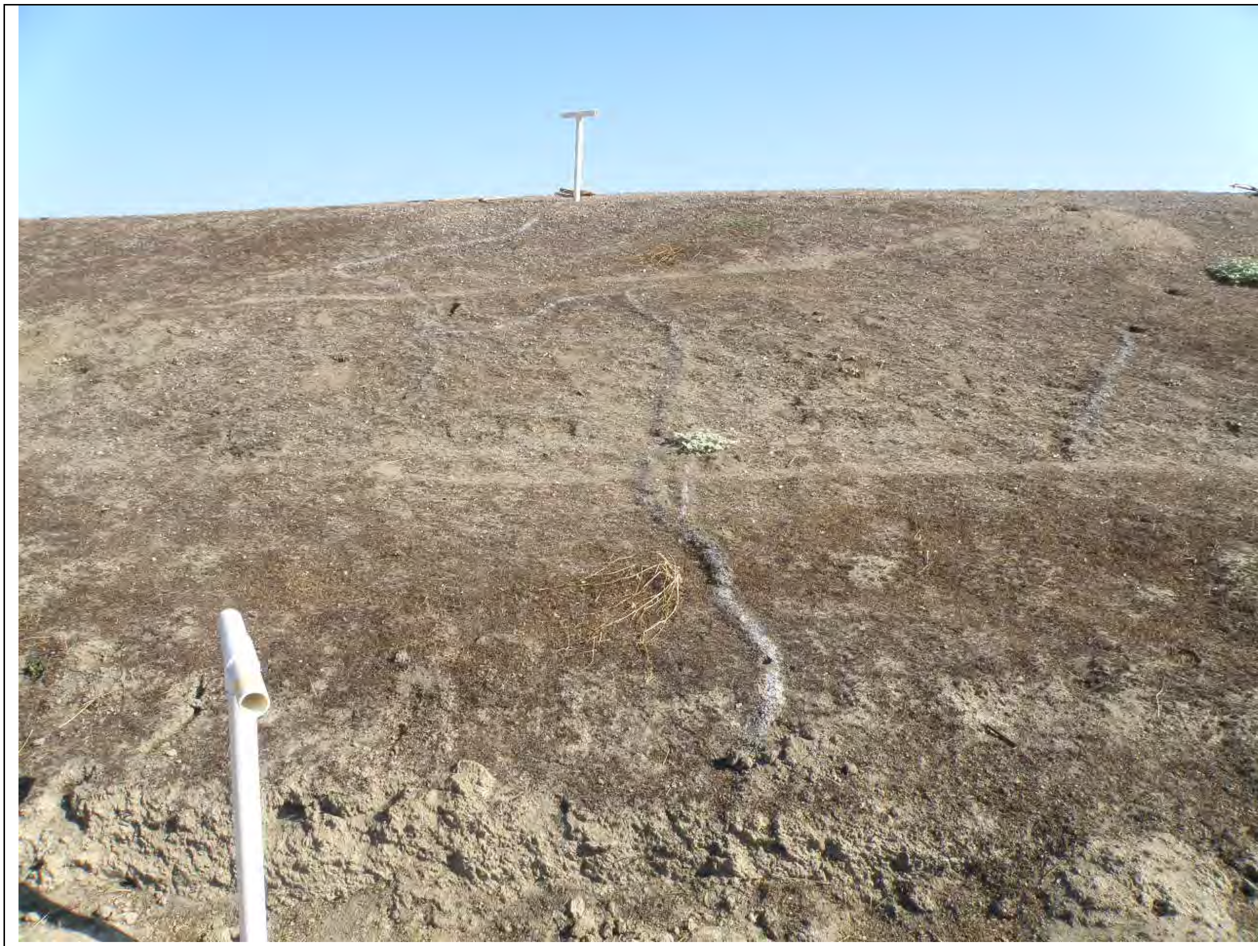

Photo 4A-3. Gopher burrows along waterside slope surface of the sandy levee. White PVC pipes were used as references for the T-Lidar scans.
Burrows were approximately 6-10 cm in diameter and protruded a few centimeters above the levee slope surface and appeared to connect to several burrows going into the levee.
Burrows were highlighted using metallic spray paint so the T-LiDAR scans could capture them.

Photo 4A-4. View of test area landside slope, sandy levee. Grid spacing 0.5 m.
Corn crop to the right of the image is likely the food source supporting the ground squirrel population. Even though there is a ditch near the landside toe, the levee segment has a series of wooden planks that allow passage of the squirrels. Corn kernels were observed a ground squirrel burrow entrance.

Photo 4A-5. Landside levee hingepoint, DWR injecting cement-bentonite grout into large burrow cavities. A crack had formed between these holes and extended several meters towards the levee centerline.

Photo 4A -6. Active ground squirrel burrow on landside slope that took over 15 minutes to grout using DWR's cement-bentonite mix.

Photo 4A -7. Insertion of urethane grout injection tubes along waterside slope, sandy levee. 1.5 m (5 ft) long steel rods were spaced 1.2 m (4 ft) along the entire site.

Photo 4A -8. Consistency of freshly mixed urethane grout (injected into an open container for testing), sandy levee. Pink dye was added to the mix so it would easily be captured by the T-LiDAR devices.

Photo 4A -9. Excavation using air-knife, Sandy Levee.

Photo 4A -10. Excavation of road base on levee crown using backhoe, Sandy Levee.

Photo 4A -10. View of ungrouted ground squirrel burrow on landside slope below road base material, Sandy Levee.

Photo 4A -11. View of newly discovered ground squirrel burrow next to large grouted burrow on waterside toe, Sandy Levee.

Photo 4A -12. Close up of ground squirrel den and small extension feature, Sandy Levee.

Photo 4A -13. View of landside ground squirrel burrow complex, Sandy Levee.

Photo 4A -14. View of intricate multi-level ground squirrel burrow complex on landside slope, Sandy Levee.

Photo 4A -15. View of landside ground squirrel burrow complex, Sandy Levee.

Photo 4A -16. Excavated landside toe showing urethane filled burrow, Sandy Levee.

Photo 4A -17. Voids within cement-bentonite grout filled with urethane grout, Sandy Levee.

Photo 4A -18. View of ground squirrel burrows (green flags) and undifferentiated burrows (pink flags) along landside slope, Clayey Levee.

Photo 4A -19. View of ground squirrel burrows (green flags) and undifferentiated burrows (pink flags) along waterside slope, Clayey Levee.

Photo 4A -20. Location of food source for ground squirrel near landside toe, Clayey Levee.

Photo 4A -21. Injection of urethane grout, Clayey Levee. Grid spacing 0.5 m

Photo 4A -22. Initial excavation of ground squirrel den near landside toe, Clayey Levee.

Photo 4A -23. Single continuous urethane-filled gopher burrow extending several meters along landside slope, Clayey Levee.

Photo 4A -24. View of interconnected urethane grouted ground squirrel and gopher burrows and previously cement-bentonite grouted burrows, Clayey Levee.

Photo 4A -25. View looking south of burrow complex along landside slope. Note proximity of food source, Clayey Levee.

Photo 4A -26. View landside burrow complex showing several large burrows extending towards the toe, Clayey Levee.

Photo 4A -27. View of completely penetrating ground squirrel burrow, waterside slope can be seen to the left of the image, Clayey Levee.

Photo 4A -28. Close up of completely penetrating ground squirrel burrow. Cement-bentonite grout along this burrow was friable and broken in several pieces, suggesting it was grouted during the early years of DWR grouting programs, Clayey Levee.

Photo 4A -30. View of partially cement-filled ground squirrel den on landside slope, connected to a urethane-filled hole, Clayey Levee.

Photo 4A -29. Group of ground squirrel dens connected to smaller gopher holes, Clayey Levee.

Photo 4A -30. View of gopher and ground squirrel burrow system on the Clayey Site. Landside slope to the right of the image.